The impact of supercritical fluids on volcanic eruptions: Linking volatile exsolution and the state change in Deccan volcanism

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Abstract

This research outlines a sequence of events that may help explain the observed state change in Deccan volcanism about 66 million years ago. Two mantle plumes may have created a reservoir of melt in the mantle that erupted to form the Deccan continental flood basalts (Glisovic and Forte, 2017). Interestingly, these plumes and the melt reservoir they produced were very buoyant. (Glisovic and Forte, 2017). My research explores the possibility that exsolved supercritical fluids helped make the plumes and the melt reservoir highly buoyant. The exsolved supercritical fluids may have been volatiles, such as carbon dioxide and water. Manga and Brodsky (2006) found that the exsolution of volatiles may increase the buoyancy of a melt and Richards et al. (2015) concluded that carbon dioxide and water may exsolve as supercritical fluids at high temperatures and pressures. Supercritical fluids typically have densities that are less than liquids (Clifford, 1999). Richards et al. (2015) and Renne et al. (2015) found that the Chicxulub impact may have caused a state change in Deccan volcanism, although the mechanism that caused this change is unknown. This research will outline how a change in tectonics may have stopped Deccan volcanism and caused a build-up of magma in the mantle. It will show how seismic waves generated by the Chicxulub impact re-started volcanic eruptions by exploring the role of supercritical volatiles in volcanic systems. This research suggests that the exsolution of volatiles as gases, liquids, and supercritical fluids in the Earth's interior plays a pivotal role in volcanic eruptions. For example, exsolved volatiles increase the permeability of the crust to volcanic eruptions. This research also explores how the density, dynamic viscosity, and thermal conductivity of carbon dioxide and water change with depth in the Earth's interior.

Deccan volcanism

The Chicxulub impact and Deccan eruptions occurred around 66 million years ago (mya). Both events have been associated with a mass extinction at the Cretaceous-Paleogene boundary that included the dinosaurs (Renne et al., 2015). The Deccan continental flood basalts consist of ~0.6-1.3 million km^3 of lava (Richards et al., 2015). Identifying the lava source has proven elusive. Now, researchers may have found the source: Glisovic and Forte (2017) have concluded that two plumes produced a melt zone that extended from ~50-80 km below the west coast of India and had a volume of ~35-40 x 10^6 km^3. Perhaps this melt zone consisted of one or more plume heads. In either case, these plumes may have produced enough melt to explain the eruption of ~0.6-1.3 x 10^6 km^3 of Deccan basalt. The surface area of the melt reservoir or plume head(s) would be ~1 x 10^6 km^2. Assuming a round shape, the diameter would be ~1000 km, which is about the same as the plume head diameter estimated by Richards et al. (2015).

The exsolution of supercritical fluids and volcanic eruptions

Supercritical fluids typically have a lower viscosity than liquids; diffusion occurs faster in supercritical fluids than in liquids; organic materials dissolve readily in supercritical water (scH_2O); supercritical carbon dioxide ($scCO_2$) is used for extractions; and supercritical fluids are used for chromatagraphy and to facilitate chemical reactions because of their properties (Clifford, 1999). Supercritical CO_2 and supercritical H_2O may catalyze chemical reactions in the Earth's interior and play a role in concentrating materials. For example, organic materials dissolve readily in scH_2O. These materials and other materials may exsolve when scH_2O changes state. Similarly, $scCO_2$ may extract materials from magma and surrounding conduits, and these materials may exolve when $scCO_2$ changes state. In short, supercritical fluids in a melt may alter the chemical composition of the melt and the surrounding materials, play a role in ore formation and deposition, oil formation and migration, and water movement in aquifers.

The decreased density (or increased buoyancy) of molten rock makes magma ascend (Fedotov et al., 2010). One way to decrease the density of rock is to melt it. For example, Fedotov et al. (2010) found that half-melted rock was 0.1 g/ml less dense than unmelted rock. Increasing the temperature of a melt may also lower its density.

The exsolution of supercritical CO_2 and supercritical H_2O may also increase the buoyancy of melts. For example, Glisovic and Forte (2017) found that the dual plumes and the resulting melt reservoir were highly buoyant. Manga and Brodsky (2006) concluded that the exsolution of volatiles could increase the buoyancy of melts. Richards et al. (2015) suggested that carbon dioxide and water may have exsolved as supercritical fluids and possibly played a role in the Deccan eruptions. Wallace and Edmonds (2011) concluded that carbon dioxide and water are major volatile components in magma and play pivotal roles in magma formation, evolution, and eruption. Supercritical carbon dioxide and supercritical water have lower densities than magma and rock (Tables 1-7), so their exsolution may increase the buoyancy of a melt. The state of carbon dioxide and water depends on pressure and temperature (Figures 1, 2 & 3).

When volatiles exsolve, they may form low-density bubbles of gas, liquid, or supercritical fluid. These bubbles may migrate upward through melt, expanding and accelerating as pressure decreases. This situation resembles an "air-lift pump." Air-lift pumps inject air into the bottom of a submerged tube to pump water and other materials from the ocean floor to the ocean surface (Stenning & Martin, 1968). Exsolved volatiles may form an analogous "volatile-lift pump" that moves magma through a conduit if exsolved volatiles are less dense than the surrounding magma. Volatile-lift pumps may help explain the 11-17 m/s magma ascent rate reported by Lloyd et al. (2014).

In addition to having lower densities, supercritical carbon dioxide and supercritical water have low dynamic viscosities relative to magma (Tables 1-7), so exsolved $scCO_2$ and exsolved scH_2O may act as lubricants. $ScCO_2$ has low thermal conductivities compared to magma and rock (Tables 1-7) and may help magma retain heat.

Lloyd et al. (2014) suggest that the ascent rate of magma controls the exsolution rate of magma. My calculations suggest that increasing the concentration of exsolved volatiles, regardless of state, increases the ascent rate of magma due to the low density (high buoyancy) of exsolved volatiles. This creates a positive feedback between rapid ascent rates of magma and the exsolution of volatiles.

Girona et al. (2015) found that volcanoes that degas large amounts of volatiles erupt frequently. They conclude that degassing clears pathways so that deep magma can migrate upward and eventually erupt. Here, I propose several mechanisms that may help explain how volatiles can clear pathways and increase the permeability of the crust so that volcanoes can erupt.

The role of carbon dioxide in volcanic eruptions

Carbon dioxide is be present in the Earth's interior for several reasons. It may be primordial or it may form from reactions of primordial materials. The subduction of organic and inorganic carbon could also lead to the formation of carbon dioxide in the earth's interior. The state of carbon dioxide varies with temperature and pressure (Figure 1). In turn, the temperature and pressure depend on the depth within the continental crust (Figure 3). The presence of magma can also influence temperature and pressure. The density, viscosity and thermal conductivity of carbon dioxide are listed in Tables 1 & 4 and are illustrated by Figures 1, 4 & 5. Exsolved carbon dioxide may increase the buoyancy of a melt, act as a lubricant, increase magma chamber overpressure, slow the solidification of melts, and, further, the escape of carbon dioxide may lead to depressurization melting.

Supercritical carbon dioxide (scCO$_2$)

At 30.95 degrees C and 73.80 bar, carbon dioxide forms a supercritical liquid that has a density of 0.470 g/ml (Table 1). At most depths in the continental crust and possibly the mantle, carbon dioxide will be present as a supercritical fluid (Table 4 and Figures 1, 4 & 5).

If a plume of magma is saturated in carbon dioxide, scCO$_2$ may exsolve as the plume rises toward the surface, due to decreased pressure. In addition to decreasing pressure triggering exsolution, the movement of the plume and contact with crystals may cause carbon dioxide to exsolve as scCO$_2$. Since the density of supercritical carbon dioxide is less than the density of continental crust and less than the density of melt in the continental crust (see below), the exsolution of scCO$_2$ will likely increase the buoyancy of a plume. Some exsolved scCO$_2$ may form a layer on top of magma and/or migrate upward without magma.

Liquid carbon dioxide

Carbon dioxide will transform from a supercritical fluid to a liquid at a depth of about 0.64 km in the continental crust. Liquid carbon dioxide has a lower density than scCO$_2$ (Table 4 and Figure 4).

Carbon dioxide gas

At depths shallower than 0.20 km in continental crust, CO$_2$ will transform into a gas (Table 4 and Figure 4). Since 44.01 grams of carbon dioxide occupy about 22.414 liters at standard temperature and pressure (STP), the transformation of scCO$_2$ into CO$_2$ gas may further increase the buoyancy of a plume or melt. Carbon dioxide may also form a gas in melts in continental crust at pressures below 5 bar and at temperatures above ~15 degrees C (Figure 1). A basaltic magma typically erupts at temperatures of 1000—1300 ^{o}C (Table 3), so the pressurization and buoyancy increase caused by carbon dioxide exsolution may be greater than expected from ambient crustal temperatures because carbon dioxide expands (becomes less dense) when heated (PV=nRT).

Viscosity

Basaltic magma has a dynamic viscosity of ~100 Pa*s (Table 3), so one expects magma to have a slow rate of ascent through the Earth. For example, Rutherford and Gardner (1999) estimated that mamga ascended at a rate of 0.001 to 0.015 m/s. However, Lloyd et al. (2014) found that magma ascended at a rate of 11-17 m/s. The dynamic viscosity of carbon dioxide in continental crust ranges from 14.446 to 201.80 uPa*s (Table 4 and Figure 5). If exsolved carbon dioxide forms a layer on conduit walls, it may act as a lubricant.

Thermal conductivity

Basaltic magma has a thermal conductivity of ~0.6 W/m*K (Table 3). In contrast, the thermal conductivity of carbon dioxide in the continental crust ranges from 0.01584 to 0.22078 W/m*K (Table 4 and Figure 5). If $scCO_2$ forms an insulating layer on top of magma, carbon dioxide may help limit heat loss from magma.

Summary: carbon dioxide and volcanic eruptions

Carbon dioxide may be present as a supercritical fluid, a liquid or a gas in continental crust (Table 4 and Figure 4). Its density ranges from 0.00187 g/ml at 0 km to 1.1216 g/ml at 29 km. The density of continental crust is 2.8 g/ml (Table 3). The density of basaltic magma is ~2.6 g/ml (Table 3). Hence, the exsolution of carbon dioxide will increase the buoyancy of magma in the continental crust. Jing and Karato (2009) estimated that a melt in the mantle would have a density of ~3.4 to ~3.7 g/ml (see their Figure 2). The exsolution of $scCO_2$ may increase the buoyancy of magma in, and, possibly, below continental crust. Hence, the highly buoyant plumes and melt reservoirs observed by Glisovic and Forte (2017), may be partially explained by the exsolution of supercritical carbon dioxide in the mantle. Further, increasing the buoyancy of magma could speed its ascent and increase the chances of eruption. The exsolved CO_2 may create a “volatile-lift pump” that transports magma upward.

Manga and Brodsky (2006) concluded that increasing magma chamber overpressure could cause volcanoes to erupt. Overpressure may remove blockages and may enable magma that had been trapped by the blockages to erupt. Further and somewhat counterintuitively, the removal of blockages may allow pressure to escape and cause depressurization melting, which would increase the chances of eruption of magma located below the blockages. Depressurization and depressurization melting play major roles in seismic exsolution (Namiki, 2016). In short, increasing pressure below a melt (magma overpressure) facilitates eruptions, while decreasing pressure above a melt also facilitates eruptions (depressurization melting). Overpressurization and depressurization may help explain the positive correlation between outgassing and eruption frequency observed by Girona et al. (2015).

Magma that has a layer of $scCO_2$ over it is susceptible to seismic exsolution (Namiki et al., 2016) and impact exsolution (Harrison, 2017). This layer may also inhibit heat loss from melts.

The role of water in volcanic eruptions

The role of water in volcanic eruptions parallels observations already made about carbon dioxide. For example, water is be present in the Earth's interior for several reasons. It may be primordial, or it may form from reactions of primordial materials. Water in the Earth's interior could also be subducted directly or formed indirectly from the reactions of subducted materials (Nishi et al., 2017). Liu et al. (2017) suggest that the subduction of hydrous minerals leads to the formation of hydrogen-bearing iron peroxide. In short, ocean water forms hydrous minerals. When subducted, these minerals release water, which reacts with iron from the core to form hydrogen-bearing iron peroxide. Iron peroxides may help explain the presence of ultralow-velocity zones near the core mantle boundary. Perhaps some of the water released by hydrous minerals does not react with iron. This water may help explain the formation of buoyant mantle plumes.

The state of water varies with temperature and pressure (Figure 2). In turn, the temperature and pressure depend on the depth within the continental crust (Figure 3). The presence of magma may also influence temperatures and pressures as previously mentioned. The density, viscosity and thermal conductivity of water are listed in Tables 2 & 5, and illustrated by Figures 2, 6 & 7. Exsolved water may increase the buoyancy of a melt, act as a lubricant, increase magma chamber overpressure, and, further, the escape of water vapor may lead to depressurization melting. Also, exsolved water may lower the solidus temperature of overlying magma (Jing and Karato, 2009; Sarafian et al., 2017).

Supercritical water (scH_2O)

At 374.15 degrees C and 221.2 bar, water forms a supercritical liquid that has a density of 0.315 g/ml (Table 2). At depths below 14.4 km in the continental crust, water is present as scH_2O (Figure 6). If a magma plume is saturated in H_2O, scH_2O may exsolve as the plume rises toward the surface and pressure decreases. The upward movement of the plume and contact with crystals may also cause scH_2O exsolution.

Liquid water

Water transitions from a supercritical fluid to a liquid at about 14.4 km in the continental crust. Above that depth, water is present as a liquid at ambient temperatures and pressures (Tables 2 and 5 and Figures 2, 6 and 7).

Water vapor

At low pressures and high temperatures, water is present as steam (Figure 2). Hot magma may transform water into steam at low pressures. Since 18 grams of water vapor occupy about 22.414 liters at STP, water vapor has the potential to greatly increase the buoyancy of magma. At higher temperatures, steam occupies a greater volume than water vapor, since PV=nRT. Hence, the formation of steam would further increase the buoyancy of a plume. Basaltic magma erupts at temperatures ranging from 1000 to 1300 ^{o}C (Table 3). Therefore, steam may form in the presence of magma at shallow depths in the continental crust. Further, steam may transfer heat to overlying magma.

Lowering the solidus temperature with water

Water lowers the solidus temperature of a melt (Jing and Karato, 2009; Sarafian et al., 2017), so if exsolved water gets added to a partially-solidified magma, it may increase the fraction of liquid melt present, making eruptions more likely. For example, if water migrated upwards to a clog of mushy or solidified melt, the solidus temperature might decrease enough to cause a partially-solidified magma clog to become liquid enough to erupt. This process would be aided by the addition of heat and pressure from the water vapor. In short, adding water to crust that contains partially solidified magma would increase the crust's permeability to volcanic eruptions.

Viscosity

Magma is viscous. For example, the dynamic viscosity of basaltic magma is 100 Pa*s (Lesher and Spera, 2015). The dynamic viscosity of water both as a liquid and SCF in the continental crust ranges from ~67 to ~1138 uPa*s (Table 5 and Figure 7). Since both liquid water and scH_2O have lower viscosities than magma, both liquid water and scH_2O may serve as a lubricant.

Thermal conductivity

Basaltic magma has a thermal conductivity of 0.6 W/m*K (Lesher and Spera, 2015). Since the thermal conductivity of liquid water and scH_2O in the continental crust ranges from 0.51227 to 0.88191 W/m*K (Table 5 and Figure 7), water does not have the potential to limit heat loss from magma like carbon dioxide.

Summary: Water and volcanism

The density of liquid water in continental crust ranges from 1.0039 at a depth of 1 km to a low of 0.91485 g/ml at a depth of 14 km; the density of scH_2O ranges from 0.83676 g/ml at a depth of 35 km to 0.90798 g/ml at a depth of 15 km (Table 5, Figure 6). Both liquid water and scH_2O are less dense than the average density of continental crust, which is about 2.8 g/ml (Table 3), less dense than basaltic magma, which has a density of 2.6 g/ml (Table 3), and less dense than melt in the mantle, which has an estimated density of ~3.4 to ~3.7 g/ml (Table 3). In summary, exsolving water as either liquid water or scH_2O may decrease the density of melt, make it more buoyant, and help explain the highly-buoyant plumes and melt reservoirs found by Glisovic and

Forte (2017). Exsolved H_2O may create a "volatile-lift pump" that moves magma up. Exsolved liquid water or scH_2O may form a layer on top of melt, which aids seismic exsolution (Namiki et al., 2016) and impact exsolution (Harrison, 2017). This would make magma reservoirs more susceptible to eruption. In addition to increasing the buoyancy of a melt, scH_2O, liquid water, or steam may increase the pressure of a melt. Some of the water vapor may escape and pressurize overlying melts and make them more susceptible to erupt via chamber overpressure (Manga and Brodsky, 2006). Paradoxically, the loss of pressure from a melt may cause decompression melting, also making a melt more likely to erupt (Namiki et al., 2016). Water also lowers the solidus temperature of a melt, making eruptions more likely. Due to its low viscosity, water may act as a lubricant. Adding water to crust that contains partially solidified magma may increase the permeability of the crust.

State change in Deccan volcanism

Richards et al. (2015) have described the state change in Deccan volcanism that roughly coincided with the Chicxulub impact. Renne et al. (2015) found that this transition occurred within 50,000 years of the impact, providing further evidence of a link between the Chicxulub impact and a state change in Deccan volcanism.

Pre-impact Deccan volcanism

A melt reservoir was located below India's continental crust at a depth that ranged from ~50 to ~80 km and occupied a volume of $\sim 35\text{-}40 \times 10^6$ km^3 (Glisovic and Forte, 2017). This reservoir is the basis for Deccan volcanism. I reason that this melt reservoir may be a plume head or combination of plume heads.

About 30% of the Deccan lava erupted from this reservoir before the Chicxulub impact (Renne et al., 2015). This pre-impact lava contained strontium, neodymium, and lead isotopes with a crustal signature (Vanderkluysen et al., 2011). The lava's crustal signature implies that the magma made an intermediate stop in the crust before erupting. Pre-impact eruptions were frequent and low-volume (Renne et al., 2015).

Transition

The key to understanding the transition between the pre-impact and post-impact Deccan volcanism is the change in dike orientation. Before the Chicxulub impact, Deccan basalt erupted from dikes having a north-south orientation, indicative of east-west extensional stresses (Richards et al., 2015). In contrast, the post-Chicxulub impact dikes have a random orientation, suggesting a decrease or lack of extensional stress (Richards et al., 2015). The absence of extensional stress created a barrier that prevented eruptions and allowed melt, volatiles, heat, and pressure to accumulate below India. It was analogous to preventing a pressure cooker from venting. Heat, melt, scCO_2, and scH_2O may have migrated upwards from the mantle melt reservoir, increasing the amount of melt in the crust and pressurizing crustal melt reservoirs. The Chicxulub impact generated seismic waves equivalent to a magnitude ~9-11 earthquake that extended from the surface to a depth of 200 km (Richards et al., 2015). Harrison (2017) hypothesized that the Chicxulub impact generated seismic waves that caused magma below India to exsolve volatiles, which, in turn, triggered an eruption of magma from the mantle reservoir that passed rapidly through the crust without interacting with the crust:

1) Seismic waves caused the exsolution of volatiles, such as carbon dioxide and water, between 0 and 200 km. Depending on the pressure and temperature, the volatiles may have exsolved as supercritical fluids, liquids, or gases.

2) Some of these volatiles escaped to the atmosphere, causing depressurization melting.

3) Some exsolved water may have migrated upward into partially solidified magma that blocked conduits to the surface. The water decreased the solidus temperature of these blockages, causing melting, and making these blockages more likely to erupt.

4) Heat transported by exsolved volatiles may have melted the magma, making it more likely to erupt.

5) Pressure from the exsolved volatiles may have forced overlying melt to erupt, clearing the path for future eruptions from the mantle and possibly causing decompression melting.

6) Exsolved volatiles may have created a “volatile-lift pump,” which helped magma ascend.

In short, the lack of extension forces stopped the eruption of lava between the pre-impact Kalsubai and Lonavala subgroups and the post-impact Wai subgroup and enabled melt, pressure, and volatiles to accumulate below India. This created a situation that is analogous to oil building up pressure below a salt dome. The Chicxulub impact created seismic waves that agitated these melts, like vigorously shaking a carbonated beverage can. This caused volatiles such as carbon dioxide to exsolve, which increased the permeability of the crust to volcanic eruptions by increasing the proportion of melt present via the addition of heat and water. The additional pressure may have forced this melt to erupt, clearing the way for magma from plumes or a magma chamber to erupt. This conduit clearing is consistent with observations made by Girona et al. (2015), who found that degassing could trigger volcanic eruptions by causing magma to ascend. Eventually, a tipping point was surpassed and the Wai subgroup formed.

Post-impact Deccan volcanism

About 70% of Deccan lava erupted after the Chicxulub impact (Renne et al., 2015). This post-impact lava contained strontium, neodymium, and lead isotopes with a mantle signature (Vanderkluysen et al., 2011). The lava's mantle signature implies that the magma did not make an intermediate stop in the crust before erupting. Further, these eruptions were low-frequency and high-volume (Renne et al., 2015). In short, the seismic waves from the Chicxulub impact triggered a melt reservoir in the mantle to erupt. The melt reservoir was pressurized and rich in volatiles.

Possible modern Deccan analog

Koulakov et al. (2013) described volcanic eruptions from the Klyuchevskoy group of volcanoes in Kamchatka, Russia, which includes the Klyuchevskoy, Tolbachik, and Bezymianny volcanoes. The 2005 eruptions may serve as a modern analog for the Deccan eruptions. At best, this could be considered a loose analog because Deccan volcanoes and the Klyuchevskoy volcanoes have different tectonic settings, and the depths of their magma sources are different. However, there are illustrative parallels.

Koulakov et al. (2013) observed a magma channel below 25 km, which they believe supplied the Klyuchevskoy group with liquid melt. This magma channel, which is in the mantle, is a possible rough analog to the Deccan mantle plumes identified by Glisovic and Forte (2017): the Klyuchevskoy channel was interpreted to be mostly liquid because of its high Vp/Vs values, and thought to bring mantle materials to the base of the crust (Koulakov et al., 2013). This channel created one magma source at a depth of 10-12 km and a second magma source near the surface. These magma sources supplied melt to the Klyuchevskoy volcano.

The pre-impact Deccan eruptions resemble the 2005 eruption of the Klyuchevskoy volcano: The lava from the Klyuchevskoy volcano flowed through complex conduits and chambers in the crust (Koulakov et al., 2013). The pre-impact Deccan eruptions' crustal signature (Vanderkluysen et al., 2011) implies that magma also made intermediate stops in the crust before erupting. In short, both the 2005 eruption of the Klyuchevskoy volcano and the pre-impact Deccan eruptions involved magma that made intermediate stops in the crust.

The post-impact Deccan eruptions resembled the 2005 Bezymianny eruption: The lava from the Bezymianny eruptions appears to have been supplied by a direct channel to the mantle source (Koulakov et al., 2013). The post-impact Deccan lava had a mantle signature (Vanderkluysen et al., 2011), also suggesting a direct connection to the magma source in the mantle. There may have been blockages in the Klyuchevskoy system that caused the mantle plume material to create a conduit directly to the Bezymianny volcano, similar to the Deccan blockage caused by changes in extensional stress. In short, both the 2005 Bezymianny eruption and the post-impact Deccan eruptions appear to have been supplied by magma that came directly from a mantle magma source.

Volatile exsolution in and below oceanic crust

So far, this paper has concentrated on volcanic systems that involve continental crust. The exsolution of volatiles in and below oceanic crust will vary due to differences in pressure, temperature, crustal thickness, temperature gradients, and pressure gradients. The pressure at the surface of continental crust, sea level, is ~1.01325 bar, while the pressure at the surface of oceanic crust (i.e., the pressure at the bottom of the ocean) is ~380 bar (Tables 4 and 6). The temperature of the oceanic crust will be about 2 degrees C, much cooler than the 15 degree temperature at the top of continental crust (Tables 3, 4 and 6). Continental crust has an average thickness of 35 km, an average temperature gradient of 25 degrees C/km, and an average pressure gradient of 274 bar/km (Table 3 and Figure 3). In contrast, oceanic crust has an average thickness of 10 km, an average temperature gradient of 40 degrees C/km, and an average pressure gradient of 294 bar/km (Table 3 and Figure 8). Table 6, Figure 9, and Figure 10 show the properties of carbon dioxide in oceanic crust. Table 7, Figure 11, and Figure 12 show the properties of water in continental crust. Although carbon dioxide gas is present at ambient conditions in continental crust, it is not present as a gas in oceanic crust, due to the increased pressure (Tables 4 & 6).

For oceanic crust, liquid carbon dioxide has a maximum density of 1.0703 g/ml at the surface of the crust and a minimum density of 1.0428 g/ml at a depth of 700 m (Table 6, Figure 9). Supercritical carbon dioxide has a maximum density of 1.395 g/ml at a depth of 800 m in oceanic crust and a minimum density of 0.97814 g/ml at a depth of 8 km in the oceanic crust (Table 6, Figure 9). Exsolving scCO_2 in oceanic crust or the mantle below oceanic crust may decrease the density of a melt, making it more buoyant.

The thermal conductivity of carbon dioxide in oceanic crust ranges from a low of 0.13618 W/m*K at a depth of 3 km to a high of 0.25024 W/m*K at a depth of 20 km, the maximum depth used in the study (Table 6, Figure 10). Since these values are less than the thermal conductivity of basalt (~0.6 W/m*K), carbon dioxide has the potential to limit heat loss from magma. The viscosity of carbon dioxide in the oceanic crust ranges from a low of 153.76 uP*s at the surface of the oceanic crust, to a high of 300.50 uP*s at a depth of 20 km, the maximum depth of this study (Table 6, Figure 10). Hence, exsolved carbon dioxide could serve as a lubricant.

For oceanic crust, liquid water has a maximum density of 1.0205 g/ml at a depth of 0.5 km and a minimum density of 0.88341 g/ml at a depth of 9 km (Table 7, Figure 11). Supercritical water has a maximum density of 1.0035 g/ml at a depth of 20 km in the mantle below oceanic crust and a minimum density of 0.86626 g/ml at a depth of 10 km at the base of the oceanic crust (Table 7, Figure 11). Exsolving water in oceanic crust or the mantle below oceanic crust may decrease the density of a melt.

The thermal conductivity of H_2O in oceanic crust ranges from a low of 0.58499 W/m*K at the surface of the continental crust to a high of 1.7003 W/m*K at a depth of 20 km, the maximum depth used in the study (Table 7, Figure 12). The viscosity of H_2O ranges from a low of 114.90 uP*s at a depth of 10 km to a high of 1608.1 uP*s at the surface of the oceanic crust. Exsolved water may serve as a lubricant. Magma has the potential to increase temperature and pressure. Since the density, thermal conductivity, and viscosity of supercritical fluids depend on temperature and pressure, presence of magma may cause the observed values to differ from those listed in the the table. For example, the density could be lower than expected, due to elevated temperatures.

Near the base of oceanic crust, H_2O transitions between a liquid and a supercritical fluid. This transition may play a role in determining the boundary between oceanic crust and the mantle.

Because of the weight of water on the top of the oceanic crust, depressurization melting is likely to be less intense in oceanic crust compared to continental crust.

Supercritical fluids and clay production on Mars

Clay minerals are abundant on Mars (Cannon et al., 2017). These minerals may have formed when supercritical carbon dioxide and supercritical water reacted with Martian basaltic crust (Cannon et al., 2017). They may also have formed when the crust reacted with steam. Clay minerals may have formed on Earth and other planets if basalt reacted with supercritical fluids. This implies that sedimentary rocks on Earth may have formed in new environments and offers a new way to interpret the geological record.

Implications for earthquakes: Can the exsolution of volatiles influence earthquake activity?

Earthquakes may cause volatiles to exsolve as gases, liquids, or supercritical fluids. Exsolved volatiles have low dynamic viscosities (Tables 4, 5, 6, 7 and Figures 5, 7, 10, 12). These volatiles may lubricate faults and influence seismicity. Schultz et al. (2018) found a positive correlation between the volume of injected fluid and seismic activity.

Core exsolution

Bendick and Bilham (2017) and Voosen (2017) suggest that changes in the Earth's rotational speed are correlated with seismic activity. These changes may cause the liquid outer core to slosh. In turn, this sloshing may cause exsolution in the outer core, which may influence geological processes. If volatiles exsolve, they may increase the buoyancy of mantle plumes. Also, exsolved volatiles may lubricate faults and influence seismic activity.

Implications for the “mush model”

Cashman et al. (2017) describe the “mush model” for understanding how slow processes associated with plate tectonics result in rapid eruptions of large magma volumes. In short, volcanic systems erupt when a “tipping point” has been surpassed. Singer et al. (2016) provide a possible “tipping point:” They concluded that recharge magma that swiftly adds volatiles, heat, and material can trigger a volcanic eruption. Lloyd et al. (2014) found that magma ascended at a rate of 11-17 m/s, quantifying the swiftness with which magma additions can occur.

Exsolved volatiles may play a key role in explaining the rapid eruptions of large volumes of melt:

1) They may increase the buoyancy of a melt by increasing the rate and force of its ascent.

2) They may heat partially solidified magma. The resulting growth in melt abundance may increase the permeability of the crust, enabling an eruption.

3) They may pressurize magma, causing it to erupt.

4) They may escape from the Earth’s surface, causing depressurization melting.

5) They may form layers on top of melts, making melt reservoirs more susceptible to seismic exsolution (Namiki et al., 2016) and impact exsolution (Harrison, 2017).

6) Exolved H_2O may lower the solidus temperature of overlying magma. The resulting magma would have a higher proportion of liquid, which would increase the permeability of the crust.

7) The exsolution of volatiles may create a “volatile-lift pump,” which accelerates the upward movement of magma.

The volatile content of plumes may play a pivotal role in volcanism. Volatiles may exsolve as supercritical fluids, liquids, or gases depending on temperature and pressure.

Implications for life

Liquid water is considered essential for life (Jones & Lineweaver, 2010). Knowing the regions in the geosphere where liquid water is present can be used to identify regions where life could exist (Jones & Lineweaver, 2010). Can supercritical water support life? If so, the regions where life could survive would be greatly expanded on Earth and in the universe. Recently, Drake et al. (2017) found evidence of fungi and sulfate-reducing bacteria at depths of 740 meters in continental crust. Perhaps evidence for life will be found at depths where only supercritical water is present.

Remaining questions

To further test this hypothesis, I would extend the data—density, dynamic viscosity, and thermal conductivity of volatiles—to depths greater than ~40 km in the Earth's interior. These volatiles include carbon dioxide, water, and methane. The roles that supercritical fluids and exsolved volatiles play in oil formation and migration, ore formation and deposition, water transport in aquifers, seismic activity and other geological and biological process should be explored.

Conclusion

This research suggests that the exsolution of volatiles as gases, liquids, and supercritical fluids in the Earth's interior plays a pivotal role in volcanic eruptions. For example, exsolved volatiles may increase the permeability of the crust. Wallace and Edmunds (2011) have concluded that carbon dioxide and water are two of the most abundant volatiles in magma and that volatiles affect the formation, evolution, and eruption of magma. Richards et al. (2015) suggest that exsolved supercritical carbon dioxide and supercritical water played a role in the Deccan eruptions. Glisovic and Forte (2017) discovered that two highly-buoyant plumes and melt reservoir formed below India about 68 million years ago. Manga and Brodsky (2006) concluded that the exsolution of volatiles could increase the buoyancy of magma. My research explored how the density, dynamic viscosity, and thermal conductivity of carbon dioxide and water change with depth in the Earth's interior. In the Earth's continental and oceanic crust, exsolved carbon dioxide and water may increase the buoyancy of a melt and act as a lubricant. Carbon dioxide may also limit heat loss. Water may lower the solidus temperature of magma. In terms of the Deccan eruption, the plumes and melt reservoir observed below India may have been highly buoyant because they exsolved volatiles in addition to their high temperatures. After 30% of the Deccan lava erupted, a decrease in extensional forces inhibited further eruptions. This caused melt, pressure, heat, and volatiles to accumulate below India, creating an opportunity for impact exsolution to trigger an eruption. The Chicxulub impact may have caused exsolution of volatiles below India, which increased the permeability of the crust. This enabled low-frequency high-volume eruptions of magma from the mantle that did not interact significantly with the crust. Hence, the formation of magma in the mantle that was volatile-rich, a change in tectonics, and seismic waves generated by the Chicxulub impact worked in concert to cause the state change in Deccan volcanism.

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Tables and Figures

Table 1. Properties of supercritical carbon dioxide.

Property	Value	Depth Below Continental Crust (km)	Ocean
Molecular Weight (g/mole)	44.01	--	--
Critical Temperature (^oC)	30.95	~0.64	~0.72 km below sea floor
Critical Pressure (bar)	73.80	~0.27	~0.73 km below sea level
Critical Density (g/ml)	0.470		

The molecular weight, critical temperature, critical pressure, and critical density for carbon dioxide were obtained from Reid et al. (1987). The depths where the critical temperatures and pressures occur for carbon dioxide were calculated numerically using data from Tables 3, 4 and 6. These depths can be calculated graphically using Figures 3 and 8, except for the critical temperature, which is below sea level, but above the surface of the ocean crust. For continental crust, carbon dioxide exists as a supercritical fluid below about 0.64 km, when the temperature rises above 30.95 ^oC. For oceanic crust, carbon dioxide exists as a supercritical fluid below about 0.72 km, where the temperature rises above 30.95 ^oC. In both cases, the pressure is already above the critical temperature at these depths.

Table 2. Properties of supercritical water.

Property	Value	Depth Below Continental Crust (km)	Ocean
Molecular Weight (g/mole)	18.015	--	--
Critical Temperature (^oC)	374.15	~14.4	~9.30 km below sea floor
Critical Pressure (bar)	221.2	~0.80	~2.21 km below sea level
Critical Density (g/ml)	0.315		

The molecular weight, critical temperature, and critical pressure data for water were obtained from Reid et al. (1987). The depths where the critical temperatures and pressures occur for water were calculated numerically using data from Tables 3, 5 and 7. These depths can be calculated graphically using Figures 3 and 8, except for the location of the critical pressure in the ocean, which is above the surface of the oceanic crust. For continental crust, water is supercritical below depths of 14.4 km. At this depth, the pressure is already above the supercritical pressure. For oceanic crust, water is a supercritical fluid below about 9.30 km. At this depth, the pressure already exceeds the supercritical pressure.

Table 3. Earth properties and values.

Property	Value	Reference
Continental Crust Thickness	~35 km	Jones & Lineweaver, 2010
Continental Crust Thermal Gradient	~25^{o}C/km	Jones & Lineweaver, 2010
Continental Crust Pressure Gradient	~274 bar/km	see table caption
Continental Crust Density	~2.8 g/ml	Jones & Lineweaver, 2010
Oceanic Crust Thickness	~10 km	Jones & Lineweaver, 2010
Oceanic Crust Thermal Gradient	~40^{o}C/km	Jones & Lineweaver, 2010
Oceanic Crust Pressure Gradient	~294 bar/km	see table caption
Oceanic Crust Density	~3.0 g/ml	Jones & Lineweaver, 2010
Mantle Thermal Gradient	~0.7^{o}C/km	Jones & Lineweaver, 2010
Mantle Pressure Gradient	~441 bar/km	see table caption
Mantle Density	4.5 g/ml	Jones & Lineweaver, 2010
Mantle Melt Density	~3.4-3.7 g/ml	Jing & Karato, 2009 (Fig. 2)
Basaltic Magma Density	~2.6 g/ml	Lesher & Spera, 2015
Basaltic Magma Temperature	1000-1300 ^{o}C	Lesher & Spera, 2015
Basaltic Magma Viscosity	~100 Pa*S	Lesher & Spera, 2015
Basaltic Magma Thermal Conductivity	~0.6 W/m*K	Lesher & Spera, 2015

The pressure gradient for the continental crust, 274 bar/km, was calculated using the gravitational constant and the average crustal density. The pressure gradient for the oceanic crust, 294 bar/km, was calculated using the gravitational constant and the average density of oceanic crust. The pressure gradient for the mantle, 441 bar/km, was calculated using the gravitational constant and the average density of mantle.

Table 4. Properties of carbon dioxide in continental crust.

Depth (km)	Temp (o C)	Pressure (bar)	Density (kg/m3)	Density (g/ml)	Viscosity (uPa*s)	Thermal Cond. (W/m*K)	State
0	15.0	1.0133	1.8718	0.00187	14.446	0.01584	gas
0.1	17.5	28.413	62.803	0.06280	15.099	0.01820	gas
0.2	20.0	55.813	179.72	0.17972	17.765	0.03057	gas
0.3	22.5	83.213	810.37	0.81037	72.513	0.09017	liquid
0.4	25.0	110.61	833.42	0.83342	76.870	0.09383	liquid
0.5	27.5	138.01	849.64	0.84964	80.134	0.09671	liquid
0.6	30.0	165.41	862.25	0.86225	82.787	0.09911	liquid
0.7	32.5	192.81	872.56	0.87256	85.040	0.10119	SCF
0.8	35.0	220.21	881.30	0.88130	87.006	0.10304	SCF
0.9	37.5	247.61	888.94	0.88894	88.755	0.10470	SCF
1	40.0	275.01	895.55	0.89555	90.334	0.10621	SCF
2	65.0	549.01	937.44	0.93744	101.13	0.11709	SCF
3	90.0	823.01	960.40	0.96040	107.93	0.12443	SCF
4	115.0	1097.0	976.17	0.97617	113.19	0.13030	SCF
5	140.0	1371.0	988.31	0.98831	117.69	0.13540	SCF
6	165.0	1645.0	998.34	0.99834	121.80	0.14000	SCF
7	190.0	1919.0	1007.0	1.0070	125.66	0.14430	SCF
8	215.0	2193.0	1014.0	1.0140	129.37	0.14900	SCF
9	240.0	2467.0	1022.0	1.0220	132.98	0.15200	SCF
10	265.0	2741.0	1028.0	1.0280	136.53	0.15600	SCF
11	290.0	3015.0	1034.0	1.0340	140.03	0.16000	SCF
12	315.0	3289.0	1040.9	1.0409	143.50	0.16395	SCF
13	340.0	3563.0	1046.6	1.0466	146.95	0.16760	SCF
14	365.0	3837.0	1052.1	1.0521	150.38	0.17119	SCF
15	390.0	4111.0	1057.5	1.0575	153.80	0.17473	SCF
16	415.0	4385.0	1062.7	1.0627	157.21	0.17821	SCF
17	440.0	4659.0	1067.7	1.0677	160.61	0.18174	SCF
18	465.0	4933.0	1072.7	1.0727	164.02	0.18520	SCF
19	490.0	5207.0	1077.5	1.0775	167.42	0.18860	SCF
20	515.0	5481.0	1082.3	1.0823	170.82	0.19197	SCF
21	540.0	5755.0	1086.9	1.0869	174.23	0.19529	SCF
22	565.0	6029.0	1091.5	1.0915	177.65	0.19858	SCF
23	590.0	6303.0	1096.0	1.0960	181.07	0.20184	SCF
24	615.0	6577.0	1100.4	1.1004	184.50	0.20507	SCF
25	640.0	6851.0	1104.8	1.1048	187.94	0.20827	SCF
26	665.0	7125.0	1109.1	1.1091	191.38	0.21144	SCF
27	690.0	7399.0	1113.3	1.1133	194.84	0.21458	SCF
28	715.0	7673.0	1117.5	1.1175	198.32	0.21769	SCF
29	740.0	7947.0	1121.6	1.1216	201.80	0.22078	SCF
30	765.0	8221.0					
31	790.0	8495.0					
32	815.0	8769.0					
33	840.0	9043.0					
34	865.0	9317.0					
35	890.0	9591.0					

At depths shallower than about 200 meters, carbon dioxide is present as a gas. At depths between ~200 meters and ~640 meters, carbon dioxide is a liquid. At depths greater than about 640 meters, carbon dioxide is a supercritical fluid (SCF). The average temperature of Earth, 15 ^{o}C (Broecker, 1985), was used for the temperature at sea level. The contemporary average pressure at sea level, 1.01325 bar, was used for the starting pressure (Andrews, 2000; Holloway & Wayne, 2010). However, the average global surface temperature and pressure has changed throughout geological time. Also, temperature and pressure vary regionally, seasonally, and even daily. The temperature in the crust was calculated using a temperature gradient of 25 ^{o}C/km (Table 3). The pressure in the crust was calculated using a pressure gradient of 274 bar/km

(Table 3). Using these temperatures and pressures, density, dynamic viscosity, and thermal conductivity were calculated using the *NIST Chemistry WebBook* (Lemmon et al., 2017). At depths greater than 29 km, the pressures or temperatures exceed the limits of the equations used in the *NIST Chemistry WebBook* (Lemmon et al., 2017). The density, dynamic viscosity, and thermal conductivity of carbon dioxide all increase with depth. The average thickness of the continental crust is 35 km (Table 3). The temperatures listed in these tables are approximations. Temperatures and pressures in the tables and figures should be considered lower limits, because the intrusion of magma may increase both heat and pressure.

Table 5. Properties of water in continental crust.

Depth (km)	Temp (oC)	Pressure (bar)	Density (kg/m3)	Density (g/ml)	Viscosity (uPa*s)	Thermal Cond. (W/m*K)	State
0	15.0	1.0133	999.10	0.99910	1137.5	0.58938	liquid
0.1	17.5	28.413	999.95	0.99995	1064.6	0.59523	liquid
0.2	20.0	55.813	1000.7	1.0007	999.35	0.60098	liquid
0.3	22.5	83.213	1001.4	1.0014	940.72	0.60663	liquid
0.4	25.0	110.61	1001.9	1.0019	887.81	0.61217	liquid
0.5	27.5	138.01	1002.4	1.0024	839.88	0.61762	liquid
0.6	30.0	165.41	1002.9	1.0029	796.29	0.62295	liquid
0.7	32.5	192.81	1003.2	1.0032	756.53	0.62817	liquid
0.8	35.0	220.21	1003.5	1.0035	720.14	0.63328	liquid
0.9	37.5	247.61	1003.7	1.0037	686.74	0.63826	lquid
1	40.0	275.01	1003.9	1.0039	656.00	0.64300	liquid
2	65.0	549.01	1003.2	1.0032	447.30	0.68500	liquid
3	90.0	823.01	999.37	0.99937	336.68	0.71745	liquid
4	115.0	1097.0	993.63	0.99363	270.98	0.74323	liquid
5	140.0	1371.0	986.67	0.98667	228.98	0.76585	liquid
6	165.0	1645.0	978.96	0.97896	200.67	0.78702	liquid
7	190.0	1919.0	970.79	0.97079	180.76	0.80722	liquid
8	215.0	2193.0	962.42	0.96242	166.26	0.82615	liquid
9	240.0	2467.0	954.01	0.95401	155.35	0.84323	liquid
10	265.0	2741.0	945.68	0.94568	146.89	0.85778	liquid
11	290.0	3015.0	937.54	0.93754	140.13	0.86923	liquid
12	315.0	3289.0	926.65	0.92665	134.56	0.87718	liquid
13	340.0	3563.0	922.08	0.92208	129.83	0.88142	liquid
14	365.0	3837.0	914.85	0.91485	125.71	0.88191	liquid
15	390.0	4111.0	907.98	0.90798	122.00	0.87876	SCF
16	415.0	4385.0	901.49	0.90149	118.59	0.87219	SCF
17	440.0	4659.0	895.38	0.89538	115.39	0.86250	SCF
18	465.0	4933.0	889.64	0.88964	112.33	0.85006	SCF
19	490.0	5207.0	884.28	0.88428	109.37	0.83523	SCF
20	515.0	5481.0	879.28	0.87928	106.48	0.81840	SCF
21	540.0	5755.0	874.62	0.87462	103.63	0.79994	SCF
22	565.0	6029.0	870.30	0.87030	100.82	0.78021	SCF
23	590.0	6303.0	866.28	0.86628	98.034	0.75953	SCF
24	615.0	6577.0	862.57	0.86257	95.273	0.73818	SCF
25	640.0	6851.0	859.13	0.85913	92.536	0.71644	SCF
26	665.0	7125.0	855.96	0.85596	89.824	0.69451	SCF
27	690.0	7399.0	853.03	0.85303	87.140	0.67261	SCF
28	715.0	7673.0	850.33	0.85033	84.487	0.65088	SCF
29	740.0	7947.0	847.85	0.84785	81.870	0.62946	SCF
30	765.0	8221.0	845.57	0.84557	79.293	0.60847	SCF
31	790.0	8495.0	843.48	0.84348	76.759	0.58799	SCF
32	815.0	8769.0	841.57	0.84157	74.272	0.56080	SCF
33	840.0	9043.0	839.32	0.83932	71.836	0.54880	SCF
34	865.0	9317.0	838.22	0.83822	69.453	0.53019	SCF
35	890.0	9591.0	836.76	0.83676	67.125	0.51227	SCF

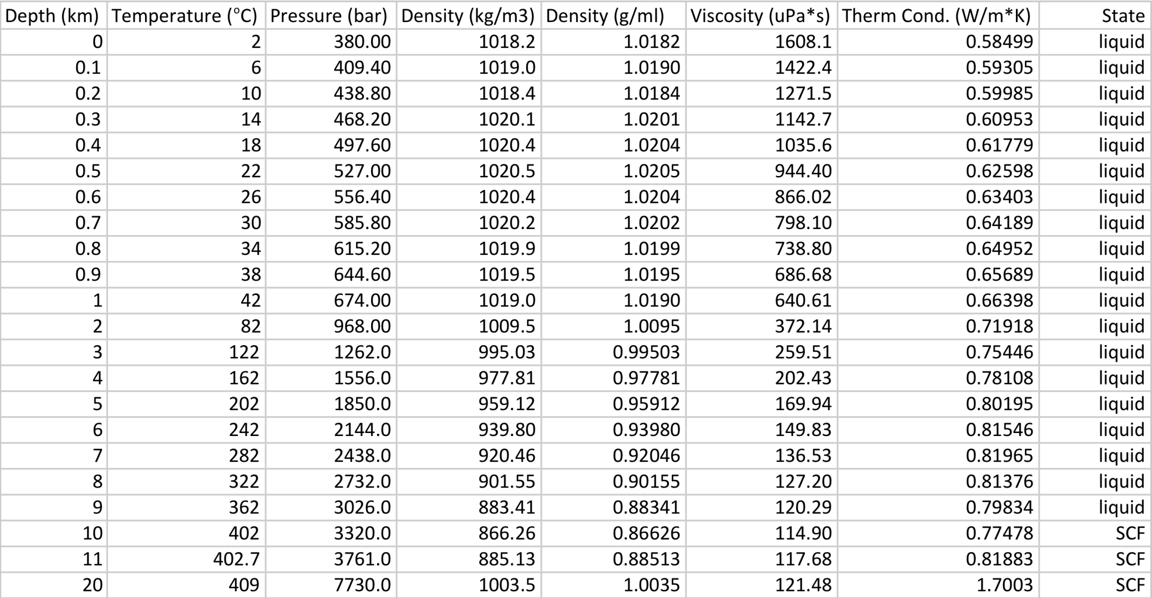
These values were calculated in the same manner as the values in Table 4. Water is present as a supercritical fluid below 14.4 km. At depths greater than 35 km, the pressures or temperatures exceed the limits of the equations used in the *NIST Chemistry WebBook* (Lemmon et al., 2017).

Table 6. Properties of carbon dioxide in the oceanic crust and mantle.

Depth (km)	Temperature (oC)	Pressure (bar)	Density (kg/m3)	Density (g/ml)	Viscosity (uPa*s)	Therm Cond. (W/m*K)	State
0.0	2.00	380.00	1070.3	1.0703	153.76	0.14742	liquid
0.1	6.00	409.40	1065.7	1.0657	150.91	0.14634	liquid
0.2	10.0	438.80	1061.4	1.0614	148.29	0.14534	liquid
0.3	14.0	468.20	1057.3	1.0573	145.89	0.14442	liquid
0.4	18.0	497.60	1053.4	1.0534	143.67	0.14357	liquid
0.5	22.0	527.00	1049.7	1.0497	141.63	0.14278	liquid
0.6	26.0	556.40	1046.1	1.0461	139.74	0.14206	liquid
0.7	30.0	585.80	1042.8	1.0428	138.00	0.14139	liquid
0.8	34.0	615.20	1039.5	1.0395	136.39	0.14078	SCF
0.9	38.0	644.60	1036.5	1.0365	134.90	0.14022	SCF
1.0	42.0	674.00	1033.6	1.0336	133.53	0.13971	SCF
2.0	82.0	968.00	1011.0	1.0110	124.28	0.13667	SCF
3.0	122	1262.0	996.90	0.99690	120.03	0.13618	SCF
4.0	162	1556.0	988.00	0.98800	118.34	0.13711	SCF
5.0	202	1850.0	982.83	0.98283	118.09	0.13893	SCF
6.0	242	2144.0	979.82	0.97982	118.70	0.14145	SCF
7.0	282	2438.0	978.41	0.97841	119.86	0.14434	SCF
8.0	322	2732.0	978.14	0.97814	121.38	0.14747	SCF
9.0	362	3026.0	978.70	0.97870	123.15	0.15075	SCF
10	402	3320.0	979.88	0.97988	125.09	0.15414	SCF
11	403	3761.0	1020.1	1.0201	139.01	0.16490	SCF
20	409	7730.0	1255.3	1.2553	300.50	0.25024	SCF

At depths shallower than about 0.72 km, carbon dioxide is a liquid. At depths greater than about 0.72 km, carbon dioxide is a supercritical fluid (SCF). The average temperature of the deep ocean, ~2 ^{o}C (Broecker and Peng, 1982), was used for the initial temperature. The average depth of the ocean is ~3800 meters (Broecker and Peng, 1982), so 380 bar was used for the initial pressure. The temperature in the oceanic crust was calculated using a temperature gradient of 40 ^{o}C/km (Table 3). The pressure in the crust was calculated using a pressure gradient of 294 bar/km (Table 3). Using these temperatures and pressures, density, dynamic viscosity, and thermal conductivity were calculated using the *NIST Chemistry WebBook* (Lemmon et al., 2017). At depths greater than ~20 km, the pressures or temperatures exceed the limits of the equations used in the *NIST Chemistry Web Book* (Lemmon et al., 2017).

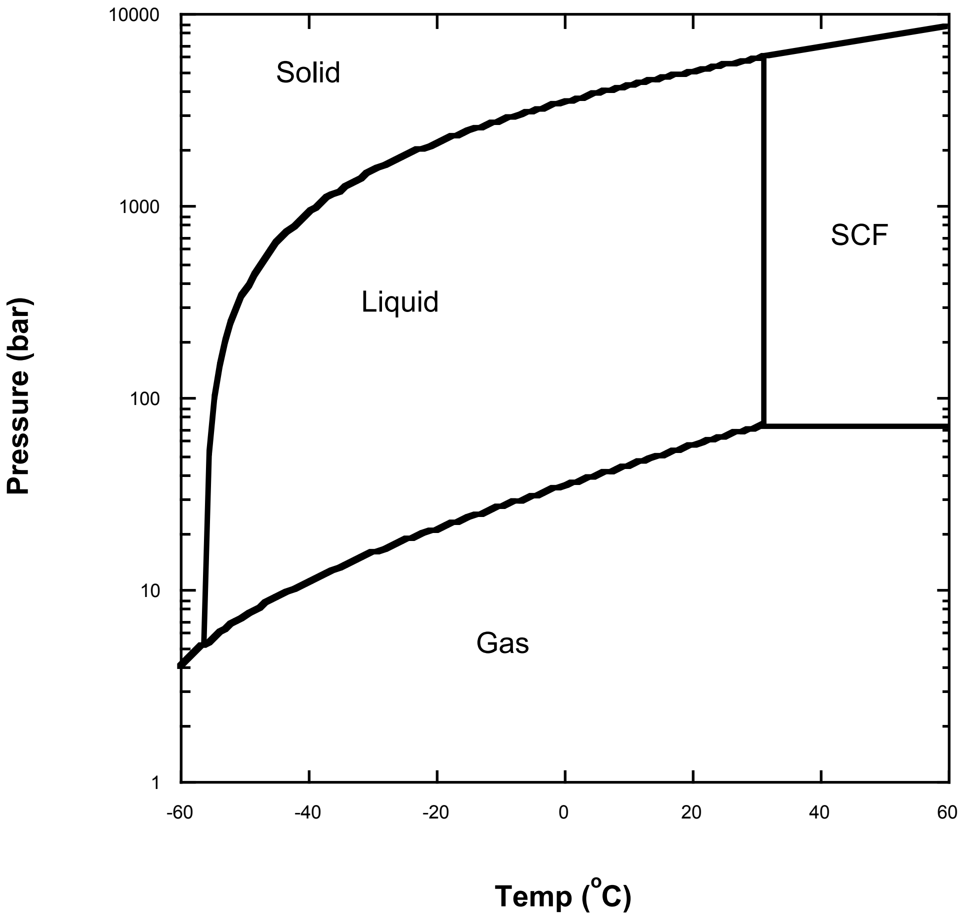
Table 7. Properties of water in oceanic crust and mantle.



Depth (km)	Temperature (°C)	Pressure (bar)	Density (kg/m3)	Density (g/ml)	Viscosity (uPa*s)	Therm Cond. (W/m*K)	State
0	2	380.00	1018.2	1.0182	1608.1	0.58499	liquid
0.1	6	409.40	1019.0	1.0190	1422.4	0.59305	liquid
0.2	10	438.80	1018.4	1.0184	1271.5	0.59985	liquid
0.3	14	468.20	1020.1	1.0201	1142.7	0.60953	liquid
0.4	18	497.60	1020.4	1.0204	1035.6	0.61779	liquid
0.5	22	527.00	1020.5	1.0205	944.40	0.62598	liquid
0.6	26	556.40	1020.4	1.0204	866.02	0.63403	liquid
0.7	30	585.80	1020.2	1.0202	798.10	0.64189	liquid
0.8	34	615.20	1019.9	1.0199	738.80	0.64952	liquid
0.9	38	644.60	1019.5	1.0195	686.68	0.65689	liquid
1	42	674.00	1019.0	1.0190	640.61	0.66398	liquid
2	82	968.00	1009.5	1.0095	372.14	0.71918	liquid
3	122	1262.0	995.03	0.99503	259.51	0.75446	liquid
4	162	1556.0	977.81	0.97781	202.43	0.78108	liquid
5	202	1850.0	959.12	0.95912	169.94	0.80195	liquid
6	242	2144.0	939.80	0.93980	149.83	0.81546	liquid
7	282	2438.0	920.46	0.92046	136.53	0.81965	liquid
8	322	2732.0	901.55	0.90155	127.20	0.81376	liquid
9	362	3026.0	883.41	0.88341	120.29	0.79834	liquid
10	402	3320.0	866.26	0.86626	114.90	0.77478	SCF
11	402.7	3761.0	885.13	0.88513	117.68	0.81883	SCF
20	409	7730.0	1003.5	1.0035	121.48	1.7003	SCF

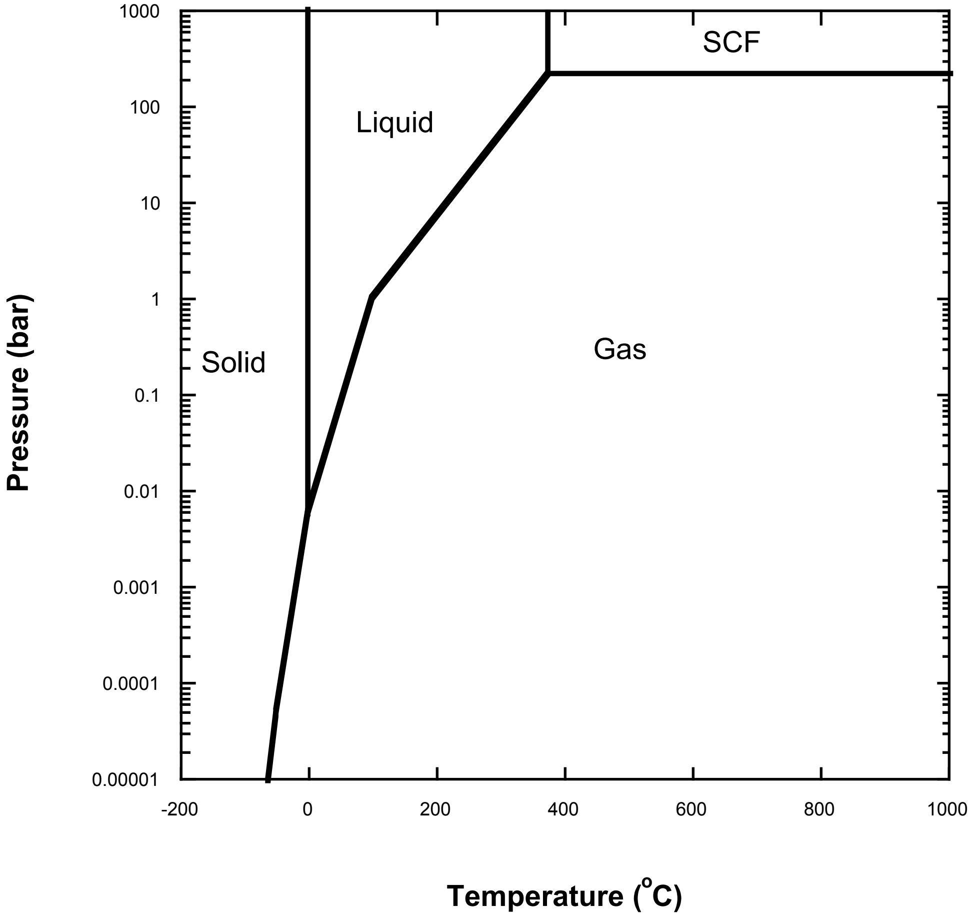
Water is a supercritical fluid below ~9.30 km. At depths greater than ~20 km, the pressures or temperatures exceed the limits of the equations used in the *NIST Chemistry WebBook* (Lemmon et al., 2017). The oceanic crust is about 10 km thick (Table 3).

Figure 1. Carbon dioxide phase diagram.



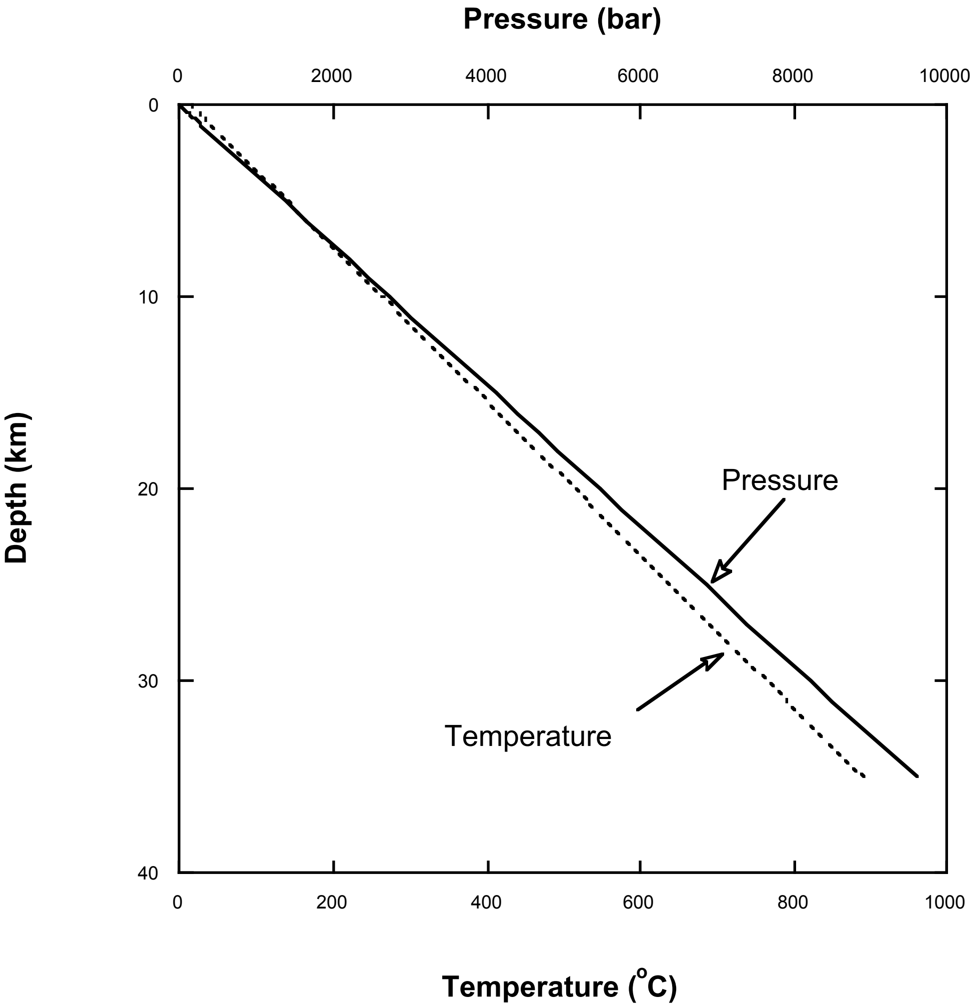
At low pressures, carbon dioxide is a gas at most temperatures in the crust and mantle. The data used to make this schematic are from Table 1, Reid et al. (1987), and Vance et al. (2015).

Figure 2. Water phase diagram.



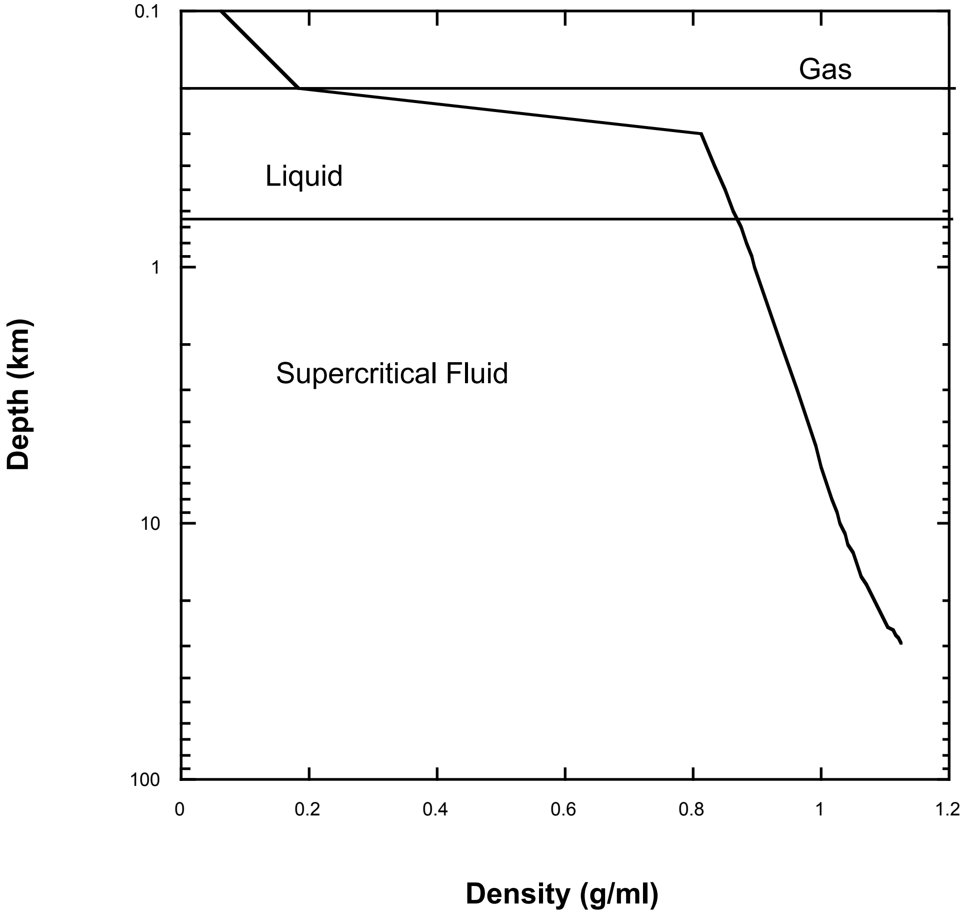
The data are from Table 2, Reid et al. (1987), and https://bg.chem.psu.edu/demos.html, accessed September 8, 2017.

Figure 3. Continental depth vs. pressure and temperature.



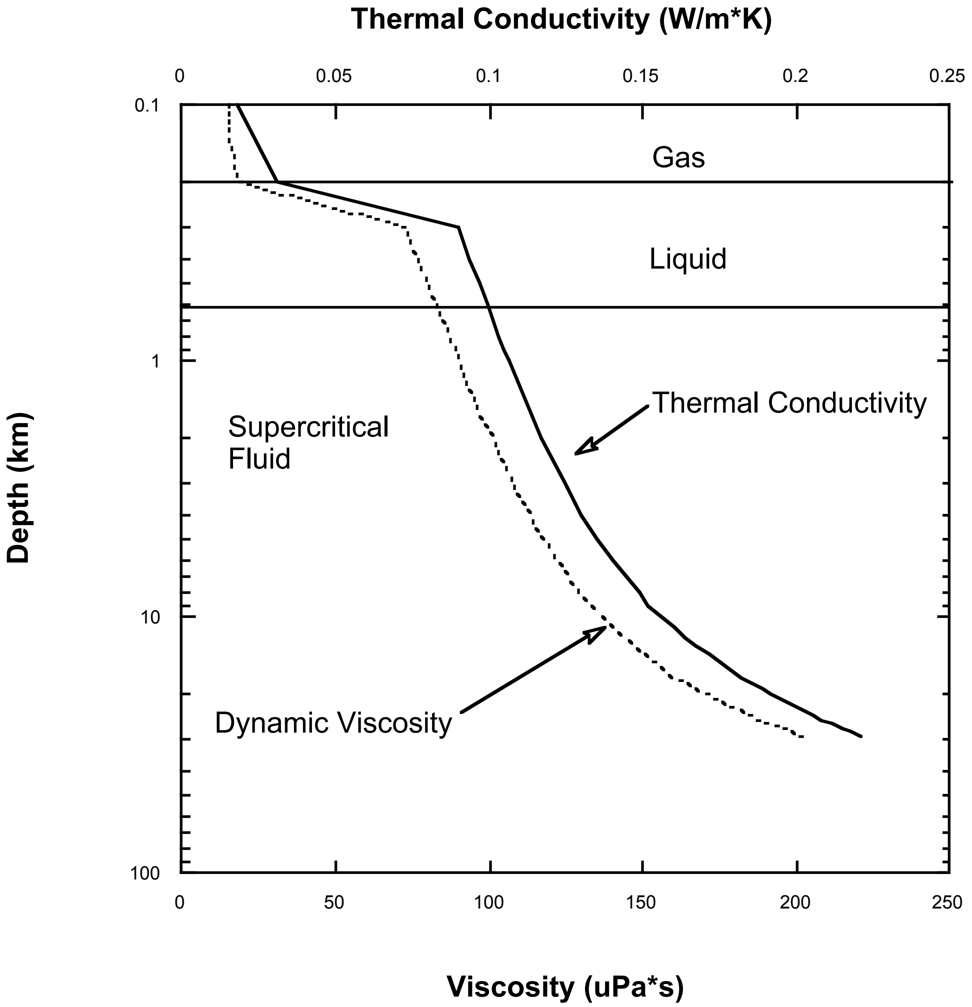
The data are from Table 4. The thickness of continental crust averages about 35 km (Table 3).

Figure 4. Continental depth vs. CO_2 density.



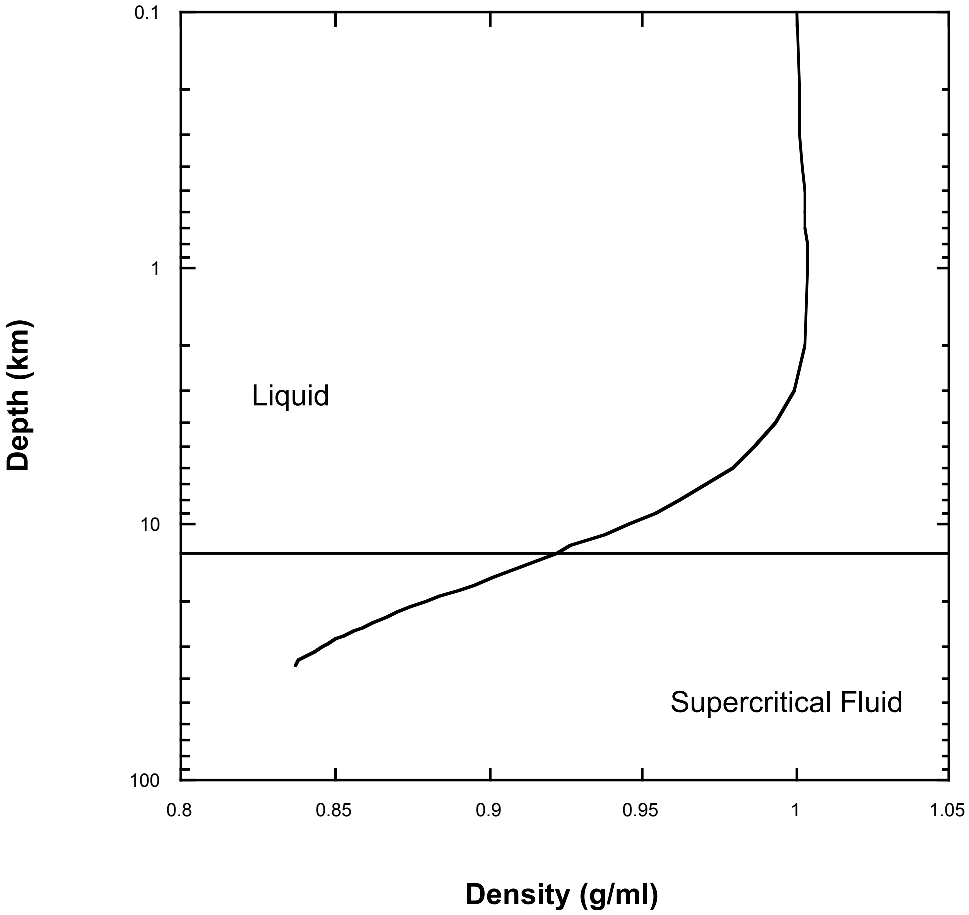
Carbon dioxide exists as a gas, liquid, and supercritical fluid below the surface of the continental crust. At depths shallower than 0.20 km, carbon dioxide is a gas. Between about 0.20 and 0.64 km, carbon dioxide is a liquid. Carbon dioxide is a supercritical fluid at depths below about 0.64 km. The density of carbon dioxide is less than the surrounding rock and may be less dense than melt, depending on the composition, temperature, and depth of the melt (Tables 3 and 4). When carbon dioxide becomes a gas, it may trigger explosive volcanic eruptions, because its volume increases as its density approaches 0.00187 g/ml at sea level (Table 4). In magma chambers, liquid or supercritical CO_2 may form a segregated layer of material, which would be subject to seismic exsolution or impact exsolution. Namiki et al. (2016) describe seismic exsolution. Harrison (2017) describes impact exsolution.

Figure 5. Continental depth vs. CO_2 dynamic viscosity and thermal conductivity.



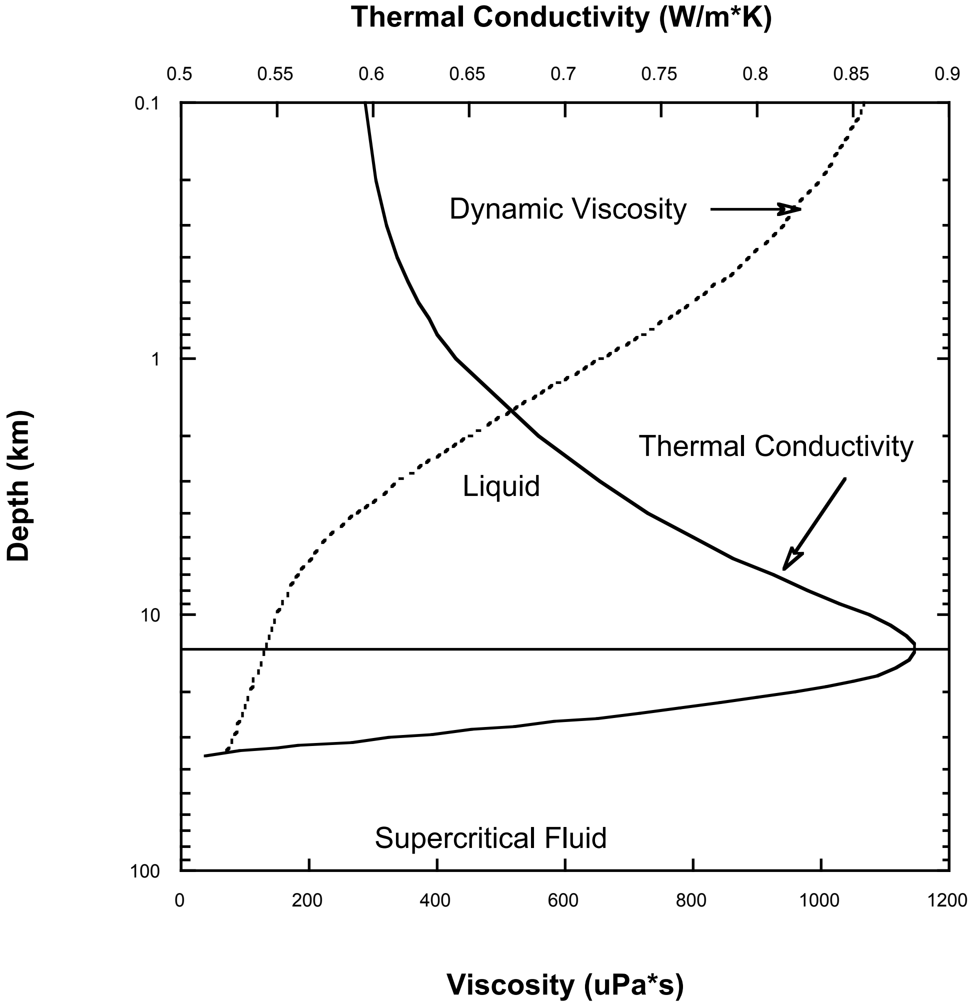
Carbon dioxide exists as a gas, liquid, and supercritical fluid below the surface of the continental crust. Compared to most rocks and melt, the thermal conductivity of carbon dioxide is low. Carbon dioxide layers may help melts retain heat. Carbon dioxide has a relatively low dynamic viscosity, which may lubricate a melt and help it to erupt. The values used for this table were taken from Table 4.

Figure 6. Continental depth vs. H_2O density.



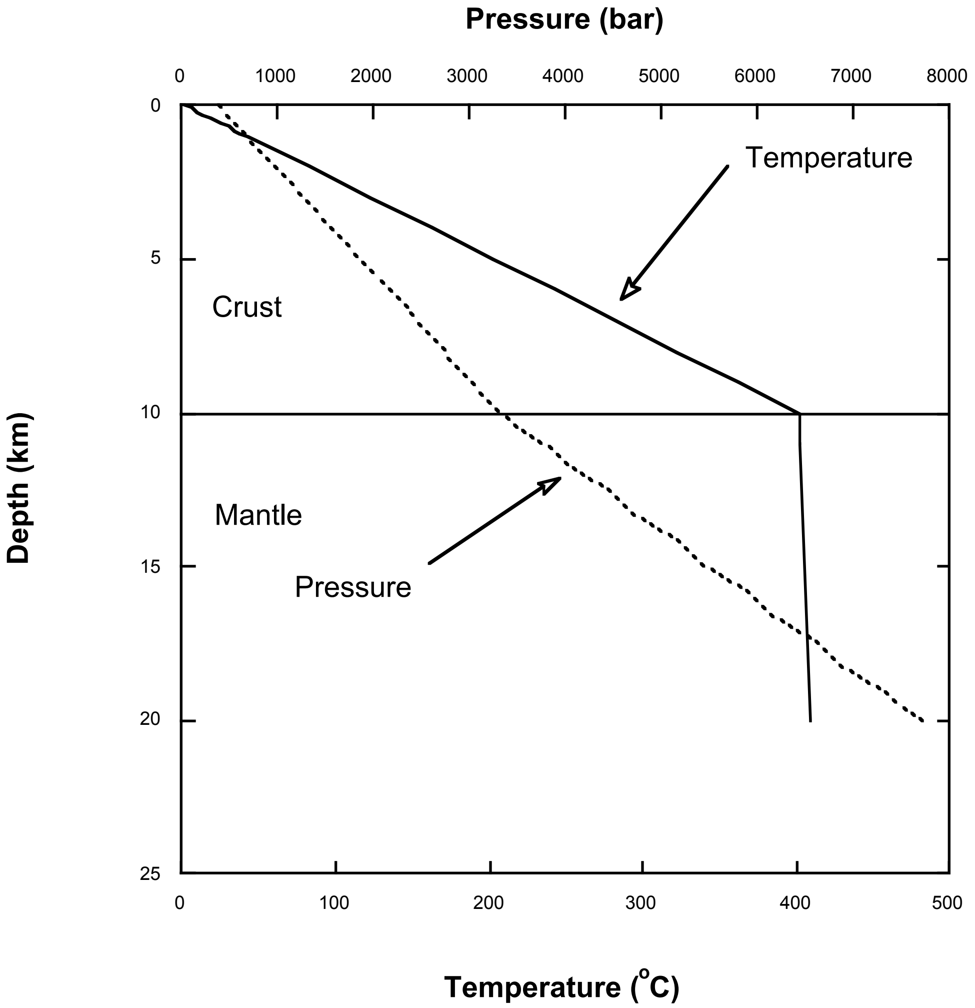
The density of liquid water hovers around 1 g/ml. The density of supercritical H_2O decreases with increasing depth. At the base of the crust, the density of scH_2O is about 0.83 g/ml. These densities are less than the surrounding rock and melt, so the exsolution of supercritical H_2O will increase the buoyancy of a melt, form layers on top of a melt, and migrate upward due to the density differences. The density stratification of scCO_2 and scH_2O increases the chances of seismic and impact exsolution. Water turns into a supercritical fluid below about 14.4 km. Data are obtained from Table 5.

Figure 7. Continental depth vs. H_2O viscosity and thermal conductivity.



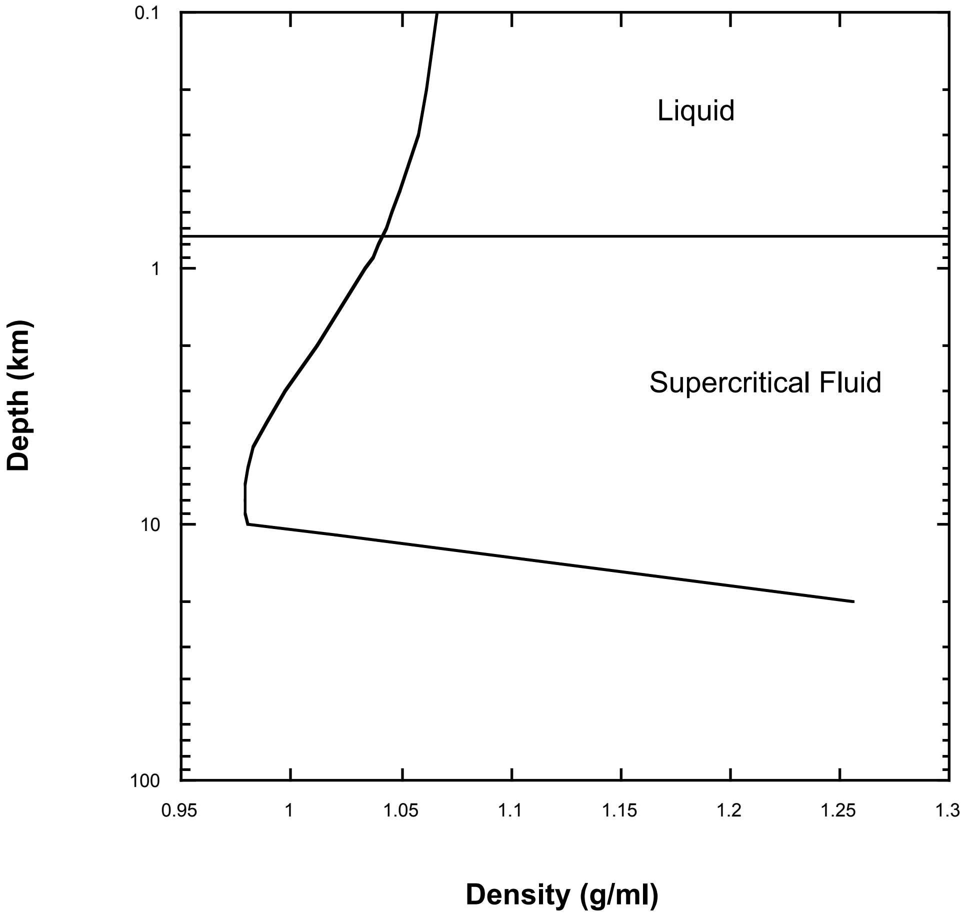
The dynamic viscosity of water decreases with increasing depth. Water may act as a lubricant to facilitate the flow of melt. Thermal conductivity achieves a maximum value at the boundary between liquid water and supercritical water. The thermal conductivity of supercritical water decreases with increasing depth. The data are from Table 5.

Figure 8. Oceanic crust temperature and pressure vs. depth.



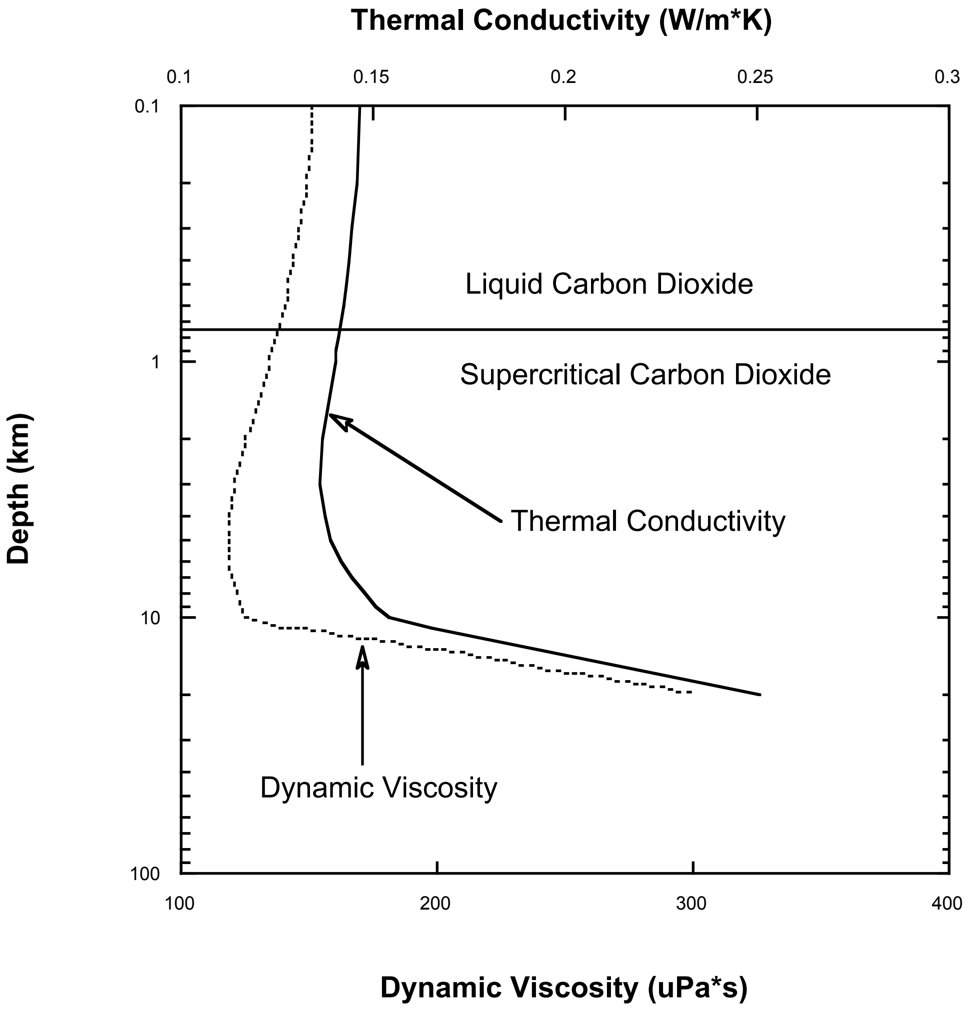
The pressure gradient increases slightly when crossing the crust-mantle boundary. The temperature gradient decreases by a large amount when crossing the crust-mantle boundary. The data are from Table 6.

Figure 9. Oceanic carbon dioxide density vs. depth.



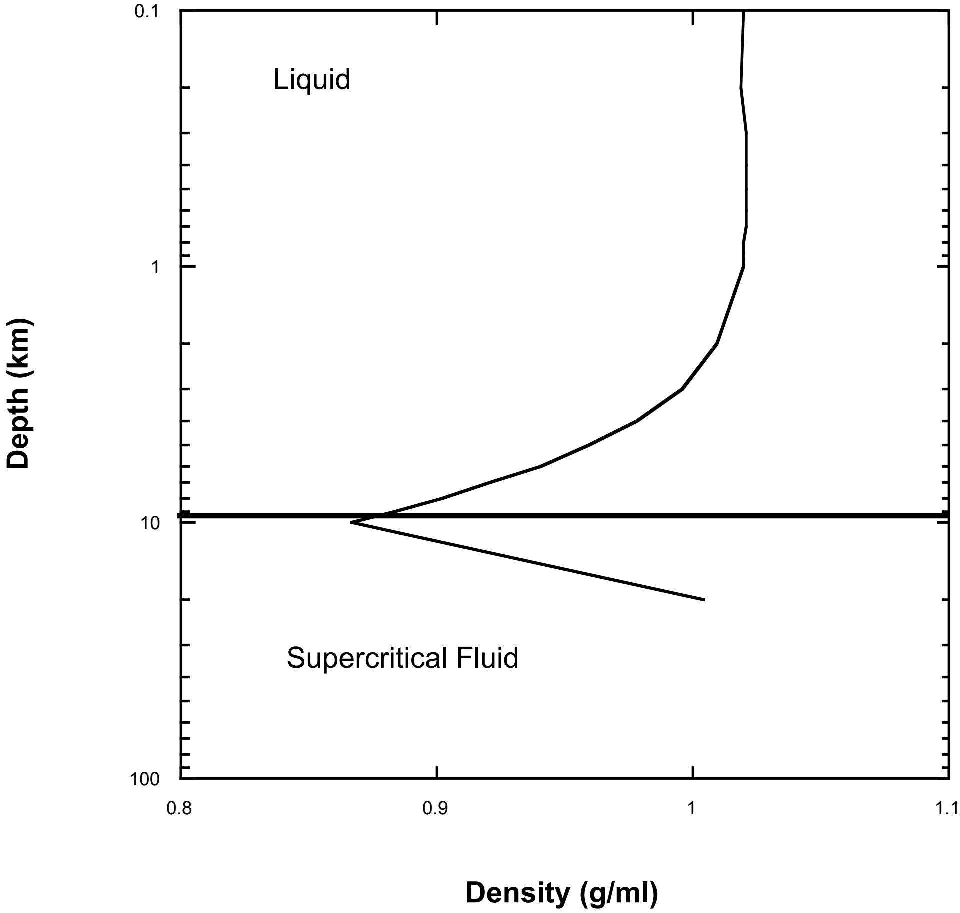
The oceanic crust is about 10 km thick (Table 3). Carbon dioxide is a liquid above 0.72 km and a supercritical fluid below 0.72 km. The data are from Table 6.

Figure 10. Oceanic carbon dioxide conductivity and viscosity vs. depth.



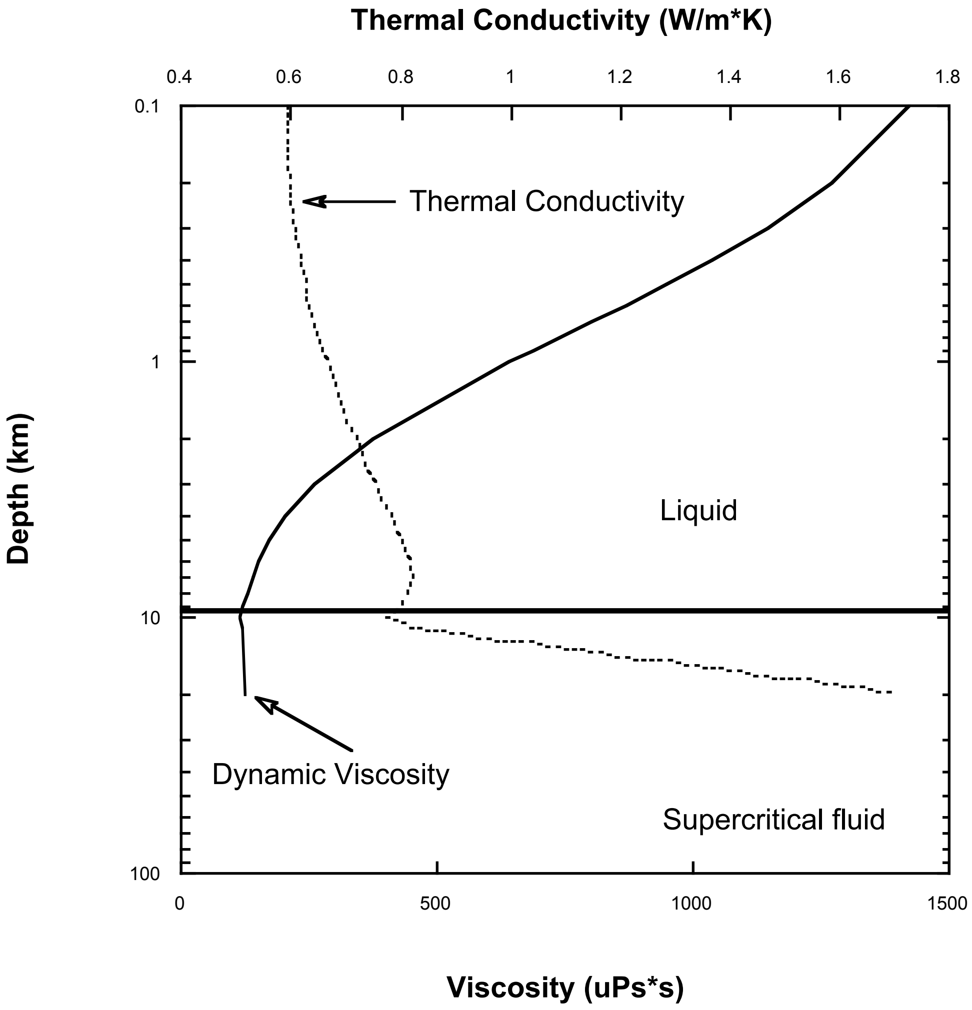
The dynamic viscosity of CO_2 changes slightly with increasing depth until about 10 km, where the viscosity starts to increase at a great rate. This transition corresponds to the base of the oceanic crust. Thermal conductivity shows the same trend. The data are from Table 6.

Figure 11. Water density vs. depth in oceanic crust.



The oceanic crust has an average depth of about 10 km (Table 3). Below about 9.30 km, water forms a supercritical fluid. The density of scH_2O increases in the mantle. The data are from Table 7. The transition between liquid and SCF, a density minimum, occurs near the base of the oceanic crust.

Figure 12. Water dynamic viscosity and thermal conductivity vs. depth in oceanic crust.



The average thickness of the oceanic crust is about 10 km (Table 3). Above 9.30 km, water is present as a liquid. Below 9.30 km, water is a supercritical fluid. Initially, both thermal conductivity and dynamic viscosity of water decrease with increasing depth. Below ~10 km, both the conductivity and viscosity of water increase. SCF and liquid H_2O may serve as a lubricant. The data are from Table 7.