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Amiata geothermal field (Italy): Modelling CO2 degassing during plant operation

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ABSTRACT

Geothermal production is often located in volcanic areas associated with natural emission of gas, among which is CO_2. The fluid produced by the geothermal plants has of course also a content of gas. The objective of this analysis is to understand, using a fluido-thermo-dynamic numerical simulator, the reciprocal impact of the plant production and of the natural emissions in the surrounding areas. The area of interest is the deep reservoir of the Amiata zone (Tuscany, Italy). The model is made of a simplified 2D reservoir and its associated cap rock. The main assumption is that CO_2 is generated at a constant rate somewhere below the reservoir where it is entering and can escape to the atmosphere.

The simulation consists in setting the natural state for which the CO_2 is expelled to the atmosphere at the same rate as it is generated. Once the plant is set in production, it is observed a gradual reduction of the natural degassing to the atmosphere up to the point where this reduction fully compensates for the plant emission. These mechanisms are of particular importance to assess the impact of the geothermal plants in terms of gas emission.

1 INTRODUCTION

Geothermal industrial production is often located in volcanic areas, accompanied by natural emissions of steam and associated gas, among which is CO_2. This is typical of historical geothermal production areas, and the same event is happening in the Apennine Tuscan area.

According to Sbrana et al. (2020), several sources were hypothesized for the anomalous deep CO_2 flux in Central Italy. Panichi and Tongiorgi (1976) suggested the hydrolysis of Mesozoic carbonates (at temperatures below 300 °C) as the main source of CO_2. Minissale (1991), Marini and Chiodini (1994), Chiodini et al. (2004), and Frezzotti et al. (2009) suggested that at least part of the CO2 is derived from the ascent of deep mantle fluids. High-grade thermos-metamorphism of graphite-rich phyllites could have led to the oxidation of graphite in phyllites and hence the release of CO_2 (Van Bergen (1983), Van Bergen and Barton (1984)). Gianelli (1985) and Orlando et al. (2010), suggested that thermo-metamorphic processes with reactions between silicates and carbonates in the metamorphic basement could have produced the CO_2. In this analysis, the hypothesis is that the generation comes from somewhere below or at the bottom of the geothermal reservoirs and is not varying with respect to the industrial times. Subsequently, it charges the system at a constant rate.

The fluid produced by the geothermal plants has of course also a content of gas. These emissions are generally quantified and reported as gas vapor ratio or gas steam ratio. The characteristics and quantities of such emissions depend on the in-situ fluid status, as well as pressure and temperature situation. They also may change with time. Moreover, it is believed that the well production interacts with the underground situation and has an influence on the natural emissions.

While recently, numerous data acquisition campaigns have started to characterize and quantify natural gas emissions of which is carbon dioxide (Sbrana et al. (2020, 2021)), historical measurements are hardly available since there is an important interest on this topic only from few years, because of the global warming concern. It is then difficult to get a quantification of their evolution with time. However, in some cases, hypothesis can be done as described in Lenzi et al. (2021), for the Larderello (Toscana, Italy) area: as mentioned above, a comparison of the current data for the geothermal power plant emissions with respect to ancient surface carbon dioxide emission data is not possible, due to the lack of registered information regarding the direct soil measurements that should have been taken during the initial phases of the utilization of the geothermal steam 200 years ago. Therefore, an indirect method has been applied, based on the data of boric acid production, available since the start of industrial development in the Larderello area and its surrounding areas. The comparison of such data shows a strong reduction of the gas emission, observed since the beginning of

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twentieth century. This reduction is comparable to the emission of geothermal plants currently running in the Larderello area, thus suggesting a decrease of natural soil emission, called 'soil emission depletion' of the same order of magnitude than the emission of the power plants. This phenomenon leads to the necessary estimation of plant emission in terms of Substitutive Emission corresponding to the actual difference between plant emission and soil emission depletion.

It is therefore interesting to understand the mechanism behind this phenomenon. This is the objective of this paper. The analysis is carried out by means of dynamic reservoir simulation, using a fluido-thermo-dynamic numerical simulator, Eclipse® 300 thermal from Schlumberger (2021).

The area of interest is the Amiata zone (Tuscany, Italy). It is a classic volcanic-intrusive geothermal system. Exploration of the Mt. Amiata area started at the beginning of the 50's, and the first overview of the geothermal system was carried out in 1970. After more than 50 years, all the data acquired during the exploration and exploitation activities allowed a significant update of this system. Data from more than 100 drillings (500-4000 m depth), as well as from many geophysical, geological, structural, and hydrogeological studies that have been carried out. It is also an historical area both for natural emissions and geothermal production. For this reason, the area is of particular interest to understand the mechanisms behind the natural degassing process and the interaction between industrial production and natural manifestation. Moreover, the data deriving from the present numerical modelling can be compared with experimental data measured in this same area by Sbrana et al. (2020, 2021).

The current study is more specifically based on the Bagnore area which is one of the two Amiata production areas and the interest is the deep reservoir. From this area, a synthetic 2D model has been set, to simplify the simulation. The reservoir is mainly liquid dominated and characterized by high pressure and temperature (circa 150 bar and 300-350°C at the reservoir top). The main component of the gas is CO_2. Basically, the process consists in charging the reservoir from the bottom by CO_2 and setting the thermal conditions to the natural state. The historical production from the wells is then applied to analyze the interaction with the reservoir in terms of CO_2 degassing.

2 MODEL GEOLOGICAL SETTING AND SIMPLIFICATION

Mt. Amiata is the largest Tuscan volcano, consisting of dacitic, rhyodacitic and minor olivine-latitic lavas that erupted in a period ranging from 300 to 190 ka. It is located on a structural high delimitated to the East by the normal (border) faults of the western side of Siena-Radicofani Neogene basin. Mt. Amiata volcanic products are mainly effusive and of silicic composition. Volcanics cover an area of about 90 km2 (see **Fehler! Verweisquelle konnte nicht gefunden werden.**, from Sbrana et al. (2020)) lying on "Tuscan" units, Oligocene-Mesozoic Ligurian units, Palaeogene Subligurian units and Neogene sediments. The volcanic activity was triggered by the activation of regional transcurrent faults following the Mio-Pliocene extensional phase that induced an important crustal thinning.

The Bagnore area (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) has two reservoirs. The shallower one (500–1500 m depth) is hosted in carbonate-evaporitic rocks belonging to the Tuscan Nappe, and locally in fractured carbonate units, the deeper one (below 2500–3000m depth) is hosted in thermo-metamorphic fractured phyllites and metasandstones of the Tuscan Metamorphic Complex, modified by thermo-metamorphic processes. The deeper reservoir is considered in this analysis (Barelli et al. (2010)).

In this area, two geothermal power plants are currently in operation, Bagnore 3 since 1999 and Bagnore 4 (group 1 and group 2) plant since end of 2014 with an installed capacity of 20 and 40 MW electric power respectively. An ORC group of 0.99MW, fed with steam, is also in exercise in the Bagnore 4 plant. These plants are the currently concurrent ones that withdraw geothermal fluid from the deeper reservoir concurring in the subtraction of carbon dioxide from the natural outflow to the surface.

To simplify the analysis and capture the main phenomenon of interest, the cap rock above the deep reservoir is in communication with atmosphere. Moreover, only a 2D section is considered to accelerate the calculation. As well, to speed up the thermal equilibrium process, the thermal rock thermal capacity is significantly reduced. The reservoir characteristics are reported in **Fehler! Verweisquelle konnte nicht gefunden werden.** below.

Two components are considered: H_2O and CO_2 and two phases: liquid and vapor. Both components can be present in the two phases and their respective composition at equilibrium is calculated by means of the K factors. Originally the CO2STORE in Eclipse® was used (Schlumberger (2021)) for which equilibrium K-values are integrated. However, temperature conditions being limited to 250°C, the K-values have been extrapolated up to 350°C which is the maximum temperature observed in the field.

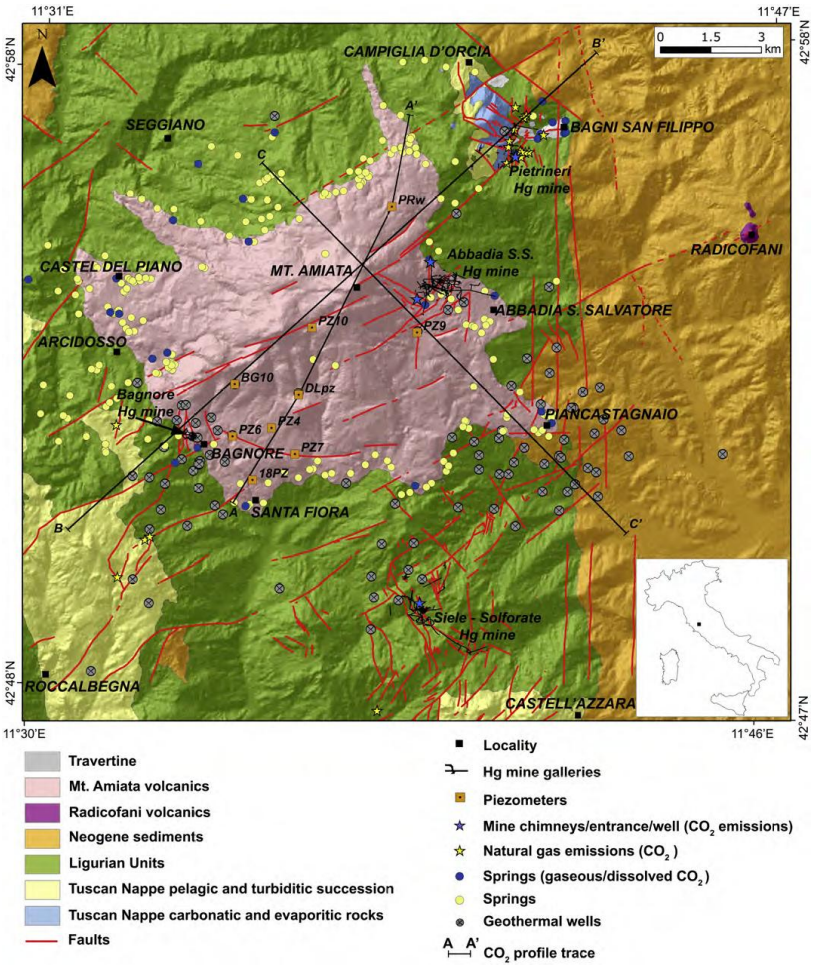


Figure 1. Monte Amiata area.

Table 1. The reservoir characteristic.

properties	units	cap rock	reservoir
Porosity	%	1	5
Permeability	mD	0.05	100
Rock thermal conductivity	kJ/ (m.d.K)	260	260
Water thermal conductivity	kJ/ (m.d.K)	6	6
Rock Heat capacity	kJ/ (m.K2)	25	25

3 SIMULATION AND RESULTS

The simulation is divided into 2 phases. The first one is the virgin situation for which the dynamic equilibrium of the system is established, both in terms of thermic equilibrium and in terms of components flow. The second one consists in setting the reservoir in production for a certain period and stopping it to evaluate how the system reacts.

3.1 Virgin equilibrium

In this study, the full process starting from a system free of CO_2 was not the focus. Subsequently, the system starts with already some CO_2 dissolved in the reservoir fluid, to accelerate the simulation time to reach the dynamic equilibrium.

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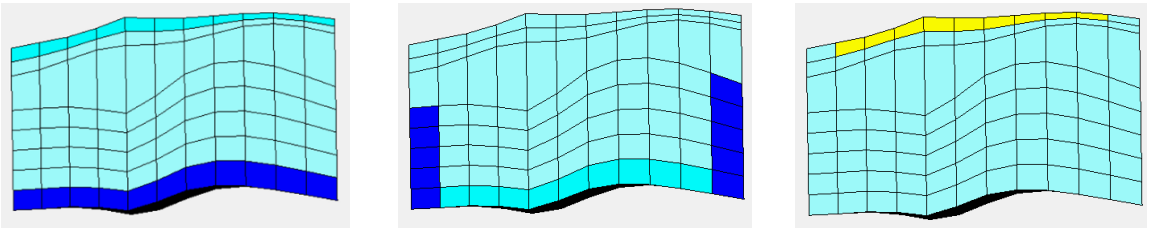
3.1.1 Boundary conditions

The first conditions are the thermic ones. A hot plate is set at the bottom of the reservoir representing the pluton hot source while the upper surface in contact with the atmosphere is set to a standard temperature (30°C). The lateral aquifer in contact with the reservoir is a constant pressure aquifer and covers the lateral edge of the reservoir. This aquifer is free of CO_2 and represents freshwater support. It is possible for the CO_2 to escape through the aquifer. At the bottom, the expected CO_2 influx is represented by an injector with constant flux. At the top of the cap rock, a gas aquifer is set allowing the CO_2 to escape to atmosphere. The characteristics of the boundary conditions are summarized in **Fehler! Verweisquelle konnte nicht gefunden werden.** below.

Table 2. Boundary conditions.

Boundary Condition	type	T	p	rate
upper	thermal	30 °C	10 bar	NA
bottom	thermal	350 °C	NA	NA
lateral	fluid	NA	200 bar @ 2300 mssTVD	free
upper	const. pressure	NA	10 bar	free
bottom	const. gas rate	NA	NA	160 t/d of CO_2

The geometrical boundary conditions are reported in **Fehler! Verweisquelle konnte nicht gefunden werden.** below.



(a) (b) (c)

Figure 2. Boundary conditions. From left to right, (a) thermal boundary conditions (dark blue at the bottom, light blue at the top), (b) dynamic: lateral aquifer (dark blue) and CO_2 influx (light blue) and (c) degassing at atmosphere (yellow).

3.1.2 Initialization

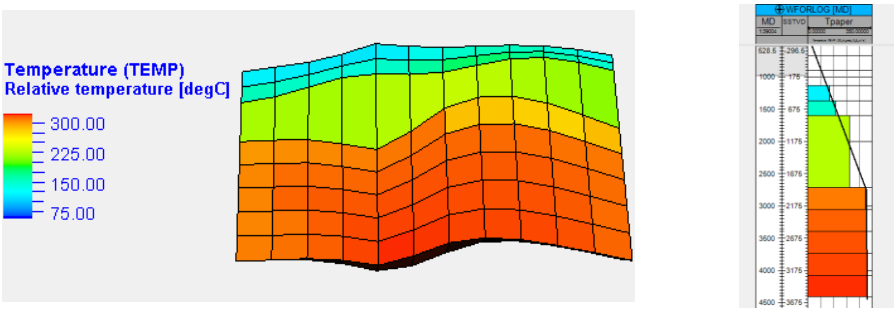
The reservoir is first set to a constant temperature, then heating takes place and finally CO_2 starts to be injected from the bottom. The rate of gas injection is based on the ground observation data acquired during different campaigns, taking also into account the current plant production as explained in the following and the similarities with the Larderello area, for which the original natural emission rates have been evaluated based on the historical boric acid production as described in in Lenzi et al. (2021). The total rate of the area is then scaled to the area of the 2D model.

3.1.3 Steady state

At dynamic equilibrium, the temperature distribution can be observed in Figure 3: nearly homogeneous in the convective zone while the classic thermal gradient is observed above in the cap rock in which the temperature declines up to a value close to the atmospheric temperature. The temperature profiles agree with the typical static log acquired in the wells of the area.

At equilibrium (steady state), the fluids are not immobile, either in the reservoir or in the cap rock. In the reservoir, due to the thermal fluid circulation (see also Todesco et al. (2010)), a water circular movement is established according to the geometry of the reservoir itself. The CO_2 is brought from the bottom to the top of the reservoir, dissolved in the water which is undersaturated. Only a small gas cap appears at the top of the reservoir. On the

opposite, the CO_2 flux in the cap rock occurs in a gas form. Indeed, in the cap rock, the petrophysical properties are much poorer compared to the reservoir ones and the water displacement would not allow the gas to escape to the surface in a liquid phase.

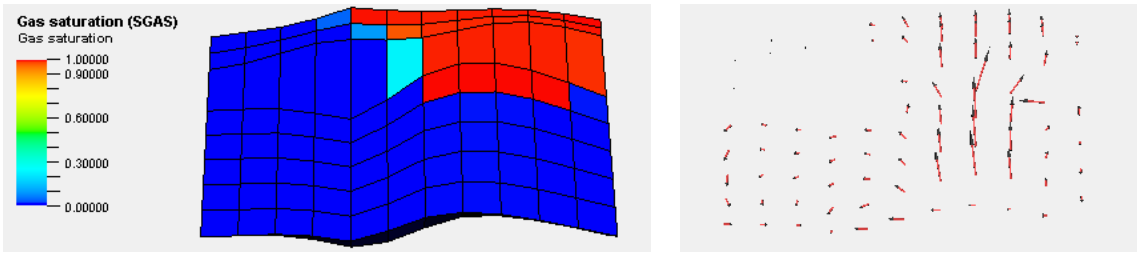


(a) (b)

Figure 3. Thermal conditions at equilibrium (a) reservoir section (b) well section.

The dissolved circular CO_2 flux is shown in Figure 4 (b) below. On Figure 4 (a), the gas saturation is reported: the reservoir is fully in a liquid phase (blue color) except at some top of it. Inside the cap rock, the fluid is in a biphasic state where the gas is escaping, and the top of the cap rock is fully gas phase (red color).

These mechanisms are critical because they agree with the observed field data. First, the data of the first wells set in production show that the fluid is initially undersaturated at the reservoir conditions such that it is recomforting to have a mechanism that brings the gas up in an undersaturated state. On the other hand, the cap rock is known to have poor reservoir qualities such that a different mechanism must take place to explain the degassing phenomena.



(a) (b)

Figure 4. Dynamic equilibrium, (a) on the left gas saturation and (b) on the right CO_2 component velocity.

3.2 Production

The production is represented by a single well completed in the reservoir below the gas cap. Water production is scaled to the area of the model, and it has been checked that the gas / brine ratio roughly respects the historically observed data. That means that the pre-production gas saturation should be representative of the virgin reservoir situation.

The evolution of the situation in the reservoir and in the caprock is described in **Fehler! Verweisquelle konnte nicht gefunden werden.** below. Starting from the left, before industrial production, it can be observed that, following the start of industrial production, there is a reduction of the CO_2 concentration in the reservoir and some places where the gas saturation disappears. Basically, the CO_2 produced by the well is recharged more rapidly by the zone below the well location and this amount of CO_2 does not charge anymore or in a less important way, remote areas of the reservoir with respect to the production one. Therefore, the degassing in atmosphere is reduced.

The CO_2 flow rates versus time are summarized in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The red line corresponds to the CO_2 quantity entering in the system from the bottom of the reservoir. As described above, this quantity is constant. The light blue line represents the atmosphere degassing rate. Before the plant

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production, this rate corresponds to the quantity entering in the system. This is the dynamic equilibrium, all the CO_2 entering is expelled into the atmosphere. The grey curve is the CO_2 produced by the plant: it corresponds to the dissolved CO_2 which is produced together with the brine / steam used for power generation. Once the plant is set in production, there is a transition period for which the natural CO_2 emissions decrease until they reach a stable value. The amount by which the degassing is reduced corresponds to the plant emission such that the total emission - natural + plant – is equal to the natural one pre-industrial production. This is as well illustrated on the right of **Fehler! Verweisquelle konnte nicht gefunden werden.** where the total emission – natural + plant- are reported. Once the plant is shut, there is a new transition period to reach again the natural state during the which the reservoir dynamic CO_2 capacity content is filled up again.

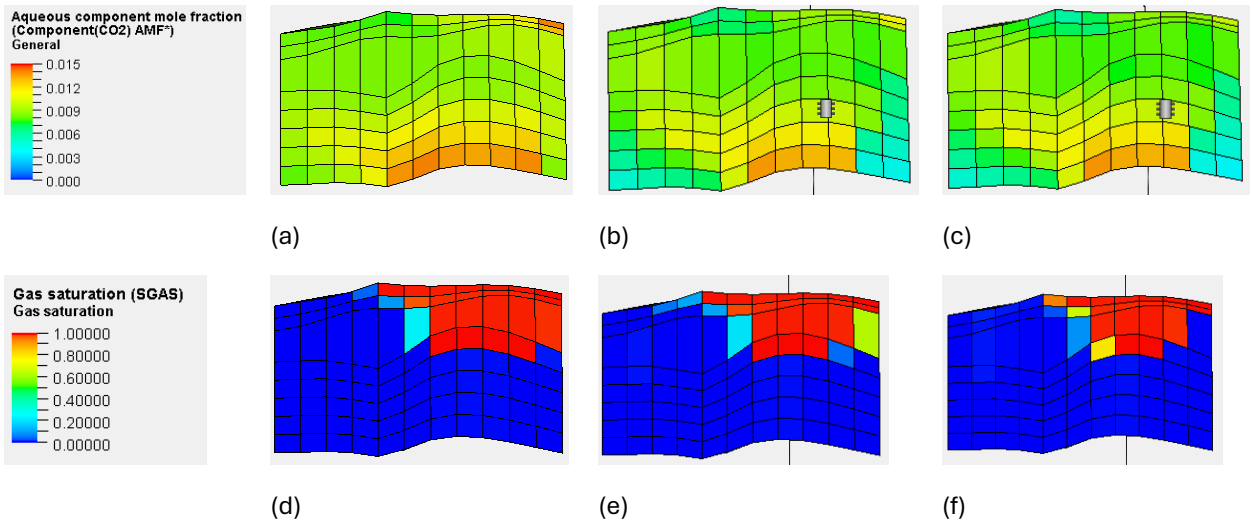


Figure 5. Top: CO_2 concentration (mole/mole), bottom: gas saturation. From the left to the right: (a) and (d) steady state pre – production, (b) and (e) Transient after some time following industrial production start – the completion is added to the section - then (c) and (f) steady state industrial production.

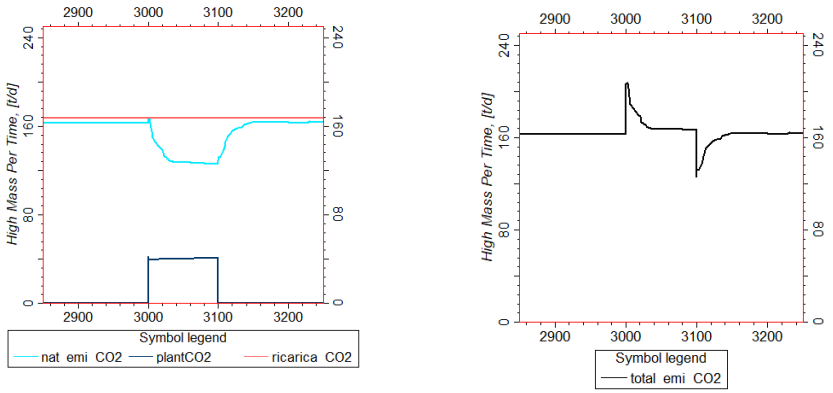


Figure 6. CO_2 gas rates. (a) recharge (red), natural emission (light blue), and plant emission (grey). (b) Total emission natural + plant.

The results presented above are quite comparable with the one described in O'Sullivan et al. (2021) for the Ohaaki New Zealand field. The simulation results show a decrease of the surface CO_2 flow close to 0 while the plant is in production (Depletion effect) followed by the gradually return to the virgin situation in 100 years circa.

Moreover, these results are in line with the natural emission analysis presented by Sbrana (Sbrana et al. (2020) and (2021)). Where a plant is present compared to a non-produced area the sum of the natural + plant is very similar to the natural ones.

In terms of timing, the result of the simulations indicates that the effect of the Depletion starts at the same time as the beginning of the industrial production. It reaches the steady state in a period of some few decades. The

profiles for the period after production show that the system is reversible, and the situation turns back to the original one in a few decades as well.

4 CONCLUSION

This paper describes the expected physical mechanism of a geothermal reservoir charged with CO_2, both for the natural state for which the diffused degassing process is reproduced and associated with dissolved CO_2 in the reservoir, and for the plant production period, to illustrate the substitution mechanism. Once a reservoir is set in production and the reservoir reaches a steady state, the plant gas emissions substitute for the natural emissions, which are reduced by the same amount, until the plant stops its production.

Of course, such synthetic simulation is a simplification of the real geology of the area, which is much more complex. For example, a preferential path such as conductive faults or interaction with other reservoirs could play a role in particular flows and timing in which the degassing occurs. However, it is believed that the main mechanisms are reproduced by these simulations.

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