



## CO<sub>2</sub> solubility in kimberlite melts



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### ABSTRACT

Carbon dioxide is the most abundant volatile in kimberlite melts and its solubility exerts a prime influence on the melt structure, buoyancy, transport rate and hence eruption dynamics. The actual primary composition of kimberlite magma is the matter of some debate but the solubility of CO<sub>2</sub> in kimberlitic melts is also poorly constrained due to difficulties in quenching these compositions to a glass that retains the equilibrium CO<sub>2</sub> content. In this study we used a range of synthetic, melt compositions with broadly kimberlitic to carbonatitic characteristics which can, under certain conditions, be quenched fast enough to produce a glass. These materials are used to determine the CO<sub>2</sub> solubility as a function of chemical composition and pressure (0.05–1.5 GPa). Our results suggest that the solubility of CO<sub>2</sub> decreases steadily with increasing amount of network forming cations from ~30 wt.% CO<sub>2</sub> at 12 wt.% SiO<sub>2</sub> down to ~3 wt.% CO<sub>2</sub> at 40 wt.% SiO<sub>2</sub>. For low silica melts, CO<sub>2</sub> solubility correlates non-linearly with pressure showing a sudden increase from 0.1 to 100 MPa and a smooth increase for pressure > 100 MPa. This peculiar pressure–solubility relationship in low silica melts implies that CO<sub>2</sub> degassing must mostly occur within the last 3 km of ascent to the surface having potential links with the highly explosive nature of kimberlite magmas and some of the geo-morphological features of their root zone. We present an empirical CO<sub>2</sub> solubility model covering a large range of melt composition from 11 to 55 wt.% SiO<sub>2</sub> spanning the transition from carbonatitic to kimberlitic at pressures from 1500 to 50 MPa.

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### 1. Introduction

Experimental investigation of the solubility of CO<sub>2</sub> in kimberlite melt has been limited due to the difficulty in quenching such melt fast enough to form a pure glass (e.g. Brey and Ryabchikov, 1994). Previous studies have therefore estimated the CO<sub>2</sub> solubility based on: (i) extrapolation from trend defined in silicate melts (Brooker et al., 2001) (ii) solubility of melt in partially to highly crystallised experiments (Brooker et al., 2011) (iii) solubility at 0.1 MPa of simple, four components, synthetic compositions considered as analogue to the natural system (Russell et al., 2012) and (iv) molecular dynamics simulation studies (Guillot and Sator, 2011). While these studies all suggest that the solubility of CO<sub>2</sub> decreases as the melt becomes enriched in silica, the effect of pressure has remained speculative. Our current knowledge from experimental studies on silicate melt suggests that CO<sub>2</sub> solubility increases with pressure (Blank and Brooker, 1994; Morizet et al., 2002, 2014; Iacono-Marziano et al., 2012) while in pure carbonate melts, CO<sub>2</sub> solubility is more related to satisfying stoichiometric requirements and therefore less dependent on pressure as

exemplified by Oldoinyo Lengai's alkali carbonatite lava (Kervyn et al., 2008). However, experiments from Wyllie (1989) and Brooker and Kjarsgaard (2011) suggest that there is some 'excess' CO<sub>2</sub> solubility in pure CaCO<sub>3</sub> melt, apparently causing a decrease in liquidus temperature.

The composition of primary kimberlite melts in term of volatile and major element chemistry is poorly constrained. Not only are natural kimberlite laden with xenolith and xenocryst (Mitchell, 2008), but the strong alteration by external fluids they typically endured, in particular serpentinization, strongly affects the volatile and major element composition (Sparks et al., 2009; Brooker et al., 2011). Latest attempt to back-calculate the kimberlite melt chemistry by removal of the serpentinization process points towards an original melt being richer in CO<sub>2</sub> and CaO and poorer in SiO<sub>2</sub>, water and MgO than calculated from "uncontaminated" kimberlites (Sparks et al., 2009; Brooker et al., 2011). This findings are corroborated with the fact that the Mg number in kimberlite is too high for equilibrium with a mantle sources (Price et al., 2000; Kopylova et al., 2007) and that liquidus temperature for "uncontaminated" kimberlite composition of 1400 °C (Brooker et al., 2011) are higher than predicted from mineral thermometry (Fedortchouk et al., 2002). We therefore chose here to follow from the work of Brooker et al. (2011) who argued that kimberlite melts are originally transitional, that is, they have a composition intermediate between a

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carbonate and a silicate liquid, and investigated several melt compositions with SiO<sub>2</sub> contents between 11 and 32 wt.%.

In this contribution, we present results on the first experimental kimberlitic glasses synthesised using an internally heated pressure vessel (IHPV) equipped with an optimised quench configuration. We produced a series of melt compositions across the “transitional” melt field (SiO<sub>2</sub> ~ 18 to ~32 wt.%) to assess the effect of silica activity on CO<sub>2</sub> solubility. The effect of pressure was then investigated by equilibrating melts of similar composition at different pressures (50 to 1500 MPa).

## 2. Experimental methodology

### 2.1. Starting material

Starting materials were produced by mixing powders from a natural lamproite from Torre Alfina, Italy (Table 1, see Peccerillo et al., 1988) with various amounts of synthetic powders of pure oxides and natural dolomite. In order to ensure homogeneity and remove the volatiles present in the Torre Alfina rock, it was fused twice in air at 1400 °C and quenched to glass. The composition of all mixtures used as starting materials of all experiments is reported in Table 1. The melt compositions we have synthesised here are very Ca-rich when compared to the more Mg-rich typical “contamination free” kimberlite (Mitchell, 1986) but later compare our findings to experiments with more Mg-rich compositions. Therefore, an underlying supposition of our work is that Mg and Ca cations behave in a similar way with respect to CO<sub>2</sub> solubility in the melt (see Brey et al., 1991; Brey and Ryabchikov, 1994 for an investigation of the effect of Mg–Ca substitution on CO<sub>2</sub> solubility in kimberlite melts and see discussion in Section 5). The Al content of the composition presented here might also be considered slightly high by some authors while the Fe content would be considered low. Notwithstanding these differences, the compositions we explored here provide a close analogue to kimberlite melts (in terms of NBO/T for instance) for which the true composition remains unknown and debated (see review by Sparks, 2013).

### 2.2. High pressure experiments; internally heated pressure vessels and piston cylinder

To investigate the solubility of CO<sub>2</sub> in transitional melts at crustal pressure, we performed a series of solubility experiments in the pressure range from 50 to 350 MPa at relatively constant temperature (1225 to 1270 °C) in relatively dry and oxidized conditions (log<sub>f</sub>O<sub>2</sub> = FMQ + 3). We used internally heated pressure vessels at the ISTO-CNRS laboratory in Orléans, which can reach pressures of up to 400 MPa (± 3 MPa) under controlled temperature up to 1300 °C (± 2 °C). The vessel was pressurised using argon gas as the pressure medium. A two-Mo-winding vertical furnace was used, creating a

5 cm isothermal (± 5 °C) “hot-spot” zone and controlled by two S-type thermocouples located on both sides of the sample.

Experimental charges consisted of anhydrous sample powder (30 to 150 mg) loaded in gold–palladium (Au<sub>80</sub>Pd<sub>20</sub>) or platinum capsules (2 to 4 cm in length, 2.5 mm inner diameter and 2.9 mm outer diameter). The capsules were welded shut. Although the initial powder mixtures were stored at 120 °C, the strongly hygroscopic character of some oxides (in particular MgO, NaO and K<sub>2</sub>O) absorbing atmospheric H<sub>2</sub>O within the 15 min necessary to load the capsules, made it impossible to obtain fully water-free experimental charges, hence lowering slightly the XCO<sub>2</sub> in the fluid in equilibrium with the melt at P & T. For each experiment, one to three capsules were hanged by a thin Pt wire. The temperature gradient along the “hot-spot” zone, where the capsules were located, was maintained at about 10 °C; the hot zone was always on the top end of the sample. This gradient, although inducing an uncertainty in the run temperature, was part of the quench optimisation strategy as it imposed a thermal profile in the furnace that ensures a strong thermal contrast over a small vertical length located directly below the hanged capsule. Rapid quenching was achieved by passing an electrical current to the holding Pt wire so that the sample dropped into the cold, bottom part of the furnace. The cooling rate was estimated at >100–200 °C s<sup>-1</sup> although no precise estimate could be obtained. After each experiment, capsules were weighed (i) before and (ii) after, opening in order to (i) verify that no leakage had occurred, and (ii) determine the amount of gas not incorporated in the glass. Capsules were then opened and a fragment of the charge was embedded in an epoxy resin and polished for SEM and microprobe analyses. We conducted a total of 18 solubility experiments. The strategy was first to produce a complete isobaric section at 350 MPa, for a range of melt chemistry spanning SiO<sub>2</sub> from 11 to 38 wt.% (expressed as nominal starting composition, Table 1). We then explored the effect of pressure on several compositions (between 17 and 38 wt.% SiO<sub>2</sub>; expressed as nominal starting composition) from 50 to 350 MPa at temperatures of 1225 to 1270 °C. While most experiments successfully produced a pure glass (Fig. 1 and Fig. S1), experiments performed at 50 MPa (run number: TA6\_1\_6 and TA7\_1\_3), one experiment at 100 MPa (run number: TA10\_1\_2) and the experiment with lowest SiO<sub>2</sub> (run number TA15\_1\_1) could not be quenched fast enough and quench crystals were present throughout the experimental charge (these crystals could not be analysed free of the glass component).

A single piston cylinder experiment was performed at 1.5 GPa and 1300 °C in a ½ inch piston-cylinder apparatus. Experimental charge consisted of natural anhydrous sample powder (30 mg) loaded in gold–palladium (Au<sub>80</sub>Pd<sub>20</sub>) capsules (1 cm in length, 2.5 mm inner diameter and 2.9 mm outer diameter). The capsule was introduced in a talc–pyrex–graphite furnace assembly and surrounded by MgO. A B-type thermocouple was located at ~1 mm atop of the capsule and the run temperature should be considered as a minimum value. The quench of the piston cylinder assembly was not fast enough to prevent the pervasive growth of quench crystals (Fig. 1; Fig. S1; experiment TA6\_1\_5).

## 3. Analytical techniques

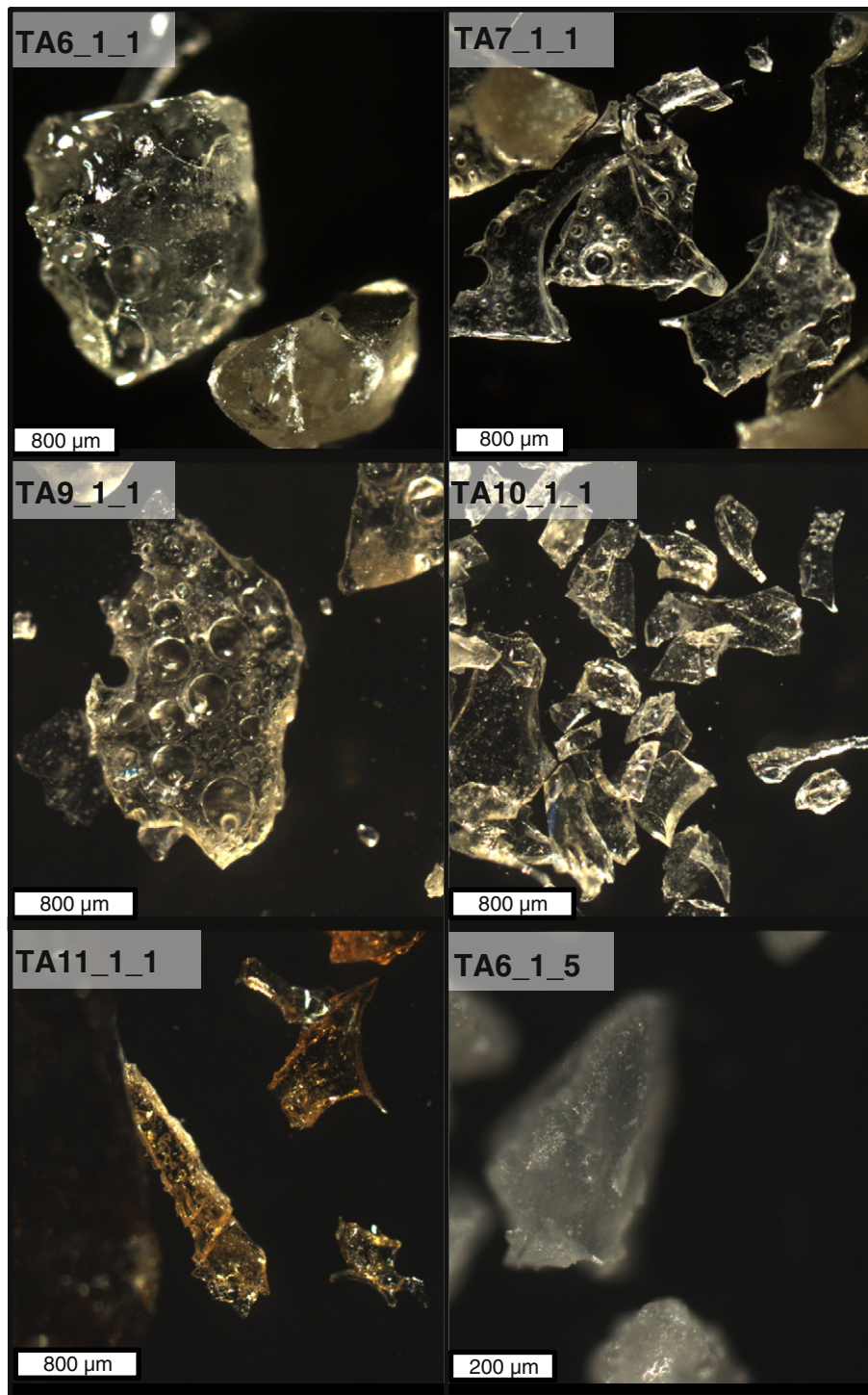
### 3.1. EMPA

All experimental products were examined by optical microscope and scanning electronic microscope (SEM) to check for the presence of quench crystals (Fig. S1). Electron microprobe analyses (EMPA) were performed on a Cameca SXFive at the ISTO-CNRS laboratory in Orléans. Glasses were analysed using an accelerating voltage of 15 kV, a beam current of 6 nA and a defocussed beam of 10 μm. Na and K were analysed first in order to minimise alkali loss during analysis. The shortfall in the totals for analysed glasses was broadly consistent with the CO<sub>2</sub> content estimated by other techniques, but systematically higher (Fig. S2).

**Table 1**

Starting oxide and natural rock powder mix compositions. The composition of a natural lamproite from Torre Alfina, Italy, (Peccerillo et al., 1988), fused twice at 1400 °C and used to prepare the oxide-mix compositions is reported at the top of the table.

Name	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	CO <sub>2</sub>	Total
TA	55.74	1.34	13.05	5.83	9.43	5.45	0.96	7.68	0.51	0.00	100
TA15	11.01	0.09	2.34	0.41	8.45	36.36	0.27	2.14	0.04	38.90	100
TA6	16.60	0.20	3.85	0.86	6.93	35.48	0.28	2.27	0.07	33.47	100
TA7	20.08	0.25	4.66	1.08	8.16	32.50	0.34	2.74	0.10	30.09	100
TA8	21.66	0.30	5.03	1.30	8.21	31.30	0.37	2.96	0.11	28.75	100
TA9	23.11	0.34	5.37	1.49	8.26	30.20	0.40	3.16	0.13	27.53	100
TA10	23.79	0.36	5.53	1.58	8.29	29.68	0.41	3.26	0.14	26.95	100
TA11	30.18	0.56	7.04	2.43	8.52	24.84	0.52	4.14	0.21	21.56	100
TA12	37.70	0.79	8.81	3.43	8.78	19.14	0.65	5.18	0.30	15.22	100



**Fig. 1.** Optical microphotograph showing the results from various supra-liquidus experimental run producing a pure glass in all cases excepted for sample TA6\_1\_5 (lower right) in which quench crystals give a “milky” aspect to the otherwise glassy product. All samples shown are synthesised in IHPV apparatus excepted sample TA6\_1\_5 which was synthesised with piston cylinder. Corresponding SEM images are shown in Fig S1.

### 3.2. Micro-Raman

We used an Innova 300-5 W Argon ion laser (Coherent©) operating at 514 nm as the light source to produce Raman scattering. Spectra were collected by a Jobin-Yvon Labram spectrometer (focal distance = 300 mm) equipped with a 2400 grooves/mm CCD detector. Analyses were performed in confocal mode (hole = 500 μm, slit = 200 μm) and using a ×50 Olympus objective reducing the analysed volume size to a few

μm<sup>3</sup>. Spectra were acquired over the aluminosilicate network and CO<sub>3</sub><sup>2-</sup> region between 200 and 1350 cm<sup>-1</sup>. In a few cases spectra were also acquired in the OH region between 2500 and 3900 cm<sup>-1</sup>. The acquisition time was of 10 × 60 s and acquisition depth was optimised in order to obtain the highest Raman signal (Mercier et al., 2009). At least three spectra were acquired for each sample. The CO<sub>2</sub> content in the glass was quantified using the calibration method of Morizet et al. (2013), which provided a reproducibility on the CO<sub>2</sub> measurements of ~5% relative,

**Table 2**

Run conditions, EMPA analyses (averaged from 20), H<sub>2</sub>O determined by elemental analyser (Flash) and CO<sub>2</sub> determined from: (i) EMPA (by subtracting H<sub>2</sub>O content to EMPA shortfall), (ii) Elemental analyser (Flash), (iii) Micro-Raman spectroscopy (following the method of Morizet et al. (2013)) and (iv) Weight loss measured by puncturing the capsule (allowing the CO<sub>2</sub> to escape) after each run. Run duration was of 2 h in all experiments.

Experiment	Pressure (MPa)	Temperature (°C)	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Total	Shortfall	H <sub>2</sub> O (Flash)	CO <sub>2</sub> (EMPA)	CO <sub>2</sub> (Flash)	CO <sub>2</sub> (Raman)	CO <sub>2</sub> (weight loss)
TA6_1_1	357.2	1225	18.44	0.2	2.05	0.74	0.03	6.87	45.25	0.3	2.3	0.04	76.22	23.8	1.54	22.24	21.84	21.4	24.4
TA6_1_4	178	1220–1260	17.97	0.19	2.63	0.81	0.04	6.75	44.8	0.41	2.19	0.04	75.83	24.2	1.19	22.98	20.07	23.4	18.9
TA7_1_1	340.2	1190	23.58	0.29	4.27	1.12	0.03	9.91	37.22	0.3	3.26	0.07	80.07	19.9	1.09	18.84	16.28	18.2	nd
TA9_1_1	336.4	1225	26.07	0.35	5.7	1.49	0.04	8.18	36.87	0.45	3.28	0.09	82.52	17.5	1.57	15.91	14.95	14.7	13.4
TA10_1_1	336.4	1225	26.77	0.35	5.8	1.64	0.05	8.52	36.24	0.4	3.39	0.09	83.25	16.8	1.73	15.02	13.80	14.4	12.0
TA11_1_1	347.8	1225	34.48	0.6	7.81	2.85	0.06	10	29.05	0.66	4.42	0.12	90.04	10.0	0.99	8.97	7.50	4.7	7.8
TA12_1_1	347.8	1225	40.97	0.82	9.74	3.68	0.06	9.38	22.96	0.82	5.58	0.19	94.19	5.8	0.59	5.22	2.79	3.5	3.7
TA6_1_5	1500	1300													1.36		24.85		nd
TA6_1_6	59.3	1225													0.84		15.87		12.7
TA7_1_2	179.2	1225	21.50	0.30	4.00	1.20	0.10	8.00	39.70	0.40	4.30	0.10	79.60	20.40	0.77	19.63	16.36	13.3	15.3
TA7_1_3	48.9	1215–1290													0.54		12.86		9.1
TA6_2_1	105.4	1270	17.80	0.20	2.40	0.70	0.10	8.10	45.20	0.20	2.50	0.10	77.20	22.80	0.79	22.01	16.47	16.3	18.3
TA7_1_4	100.7	1225	20.40	0.40	3.00	1.20	0.00	7.10	43.30	0.50	3.80	0.10	79.80	20.20	0.76	19.44	15.09	17.1	13.0
TA9_1_2	100.7	1225	24.50	0.50	4.40	1.90	0.00	8.10	39.80	0.50	4.20	0.10	84.20	15.80	0.59	15.22	10.12	10.8	11.0
TA15_1_1	351	1225													1.60		28.63		31.4
TA10_1_2	101	1225													0.71		9.00	10.18	8.59
TA11_1_2	101	1225	34.68	0.96	9.87	3.95	0.05	8.20	26.50	0.67	6.31	0.22	91.42	8.58	0.50	8.08	2.58	2.37	2.09
TA12_1_3	101	1225	43.16	0.85	9.82	3.80	0.06	9.85	22.09	0.96	5.74	0.23	96.57	3.43	0.56	2.87	1.02	1.35	1.55

corresponding to an estimated absolute error on the CO<sub>2</sub> measurements less than 1 wt.% for the investigated samples.

### 3.3. Elemental analyser

We used a Thermo Scientific, Flash 2000, CHNS elemental analyser to measure water (as H) and CO<sub>2</sub> (as C) in all experimental products. About 1 mg of sample was loaded together with 1 mg of vanadium pentoxide in a tin capsule folded and analysed by combustion at 1800 °C. The analyser was calibrated directly prior to analysis and reproducibility on external standards (marble, dolomite and hydrated basalt) was found to be better than 2% for C and 10% for H, giving an estimated error on the CO<sub>2</sub> measurement of <1 wt.%.

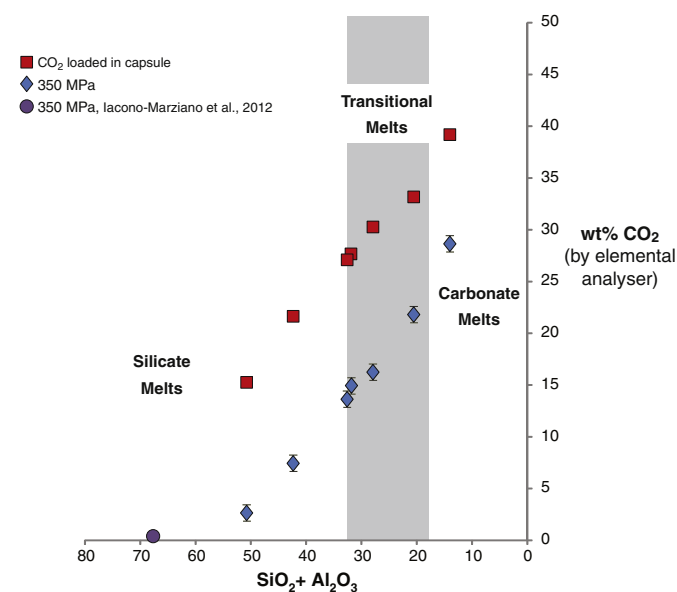
### 3.4. Gravimetric weight loss

After experiments the capsules were weighed using a high precision balance before and after puncture, to measure the mass of CO<sub>2</sub> (± H<sub>2</sub>O) in the excess fluid phase from which, the mass of dissolved CO<sub>2</sub> in the glass can be calculated by mass-balance. The error associated with this technique depends largely on the initial amount of material loaded in the capsule. Considering a maximum error on the weight measurements of 0.5 mg, for a minimum amount of loaded material of 30 mg, the error on the subsequent CO<sub>2</sub> estimate by this method is <2 wt.%. There may also be an under-estimation of fluid phase mass if some is retained in enclosed bubbles. However, most vesicles are found at the capsule wall (see Fig. 1); as a result, most of the fluid must be released on piercing.

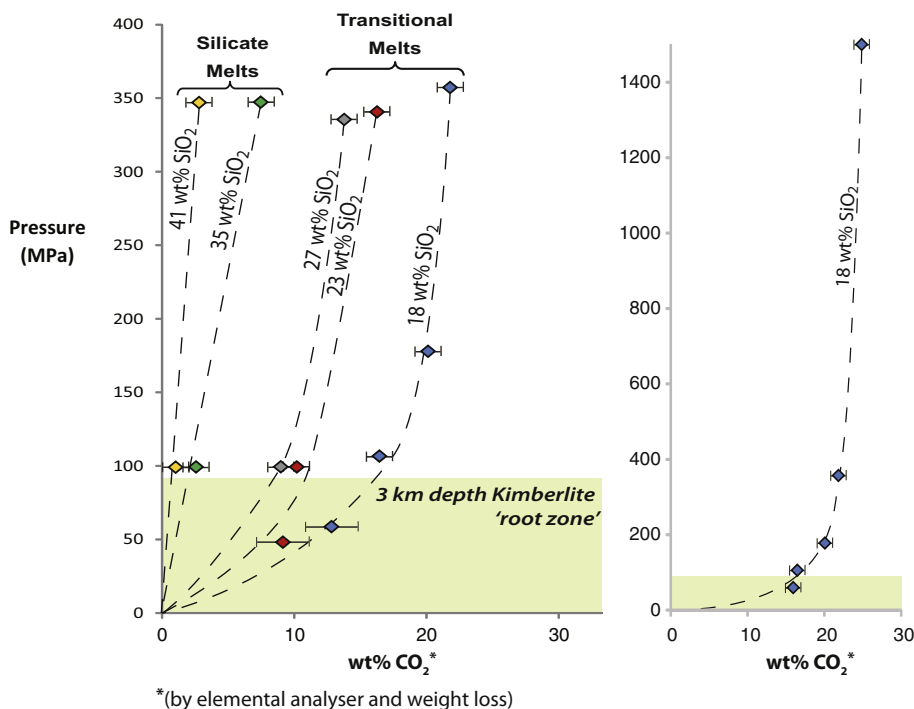
## 4. Results

All experimental charges were CO<sub>2</sub> saturated. This was attested by the presence of bubbles in all investigated charges (Fig. 1) and by weight loss after piercing the capsules. All results from solubility experiments are reported in Table 2 with CO<sub>2</sub> content estimated from elemental analyser, weight loss (after capsule puncture), EMPA and micro-Raman spectroscopy. A comparison of the four different methods used to measure the CO<sub>2</sub> content of the experimental charges is presented in Fig. S2. This figure shows that the agreement between the Raman, elemental analyser and gravimetric weight loss methods is very good. Estimates from EMPA shortfall are consistently overestimating the

amount of CO<sub>2</sub> even after correction for H<sub>2</sub>O (determined by elemental analyser), suggesting that using EMPA shortfall to estimate the melt CO<sub>2</sub> content might be inaccurate. Unless stated otherwise, all CO<sub>2</sub> contents reported in the following figures are from measurements using the elemental analyser. The results of CO<sub>2</sub> solubility experiments at 350 MPa for a range of compositions are reported in Fig. 2 together with a data point from an earlier study using a similar composition (Iacono-Marziano et al., 2012). Fig. 2 clearly shows a decrease in CO<sub>2</sub> solubility with increasing amount of network forming cations (Si<sup>4+</sup> and Al<sup>3+</sup>). This decrease appears to be smooth and continuous across the transitional field. The effect of pressure, that is nominally the pressure of CO<sub>2</sub>, on solubility is shown in Fig. 3 for starting compositions at 18 to 41 wt.% SiO<sub>2</sub> (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> of 21 to 51 wt.% respectively, expressed with volatiles at saturation at 350 MPa). Since experiments at 50 MPa



**Fig. 2.** CO<sub>2</sub> solubility measurements for a series of compositions across the silicate to carbonate melt transitions equilibrated at 350 MPa. The SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> content is reported including volatiles. For most experiments, CO<sub>2</sub> content is estimated from elemental analyser and associated error is estimated at ± 1 wt.%. CO<sub>2</sub> content from Iacono-Marziano et al. (2012) is estimated from FTIR analyses.



**Fig. 3.** CO<sub>2</sub> solubility as a function of pressure for three kimberlite/transitional and two silicate melt compositions spanning SiO<sub>2</sub> content of 18 to 41 wt.% and SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> content of 21 to 51 wt.% respectively (calculated including volatiles and corresponding to SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> contents of 27 to 54 wt.% on a volatile-free basis). The light-brown to green colour part of the plot represents the upper 3 km of crust, corresponding to the typical “root zone” of kimberlites. Dashed lines are fitted by eye through the data points.

could not be quenched fast enough to prevent the growth of quench crystals, CO<sub>2</sub> solubility was estimated from the amount of gas released after capsule puncture and their CO<sub>2</sub> contents are therefore associated with a larger error (estimated at  $\pm 2$  wt.%) than those determined by elemental analyser (estimated at  $< 1$  wt.%). At 18 wt.% SiO<sub>2</sub> (at the edge of the carbonate field) a pressure drop from 1500 to 180 MPa seems to have a limited effect on the solubility of CO<sub>2</sub> (25 to 20 wt.% CO<sub>2</sub>) and most of the solubility drop takes place from 100 to 0.1 MPa (assuming no CO<sub>2</sub> remains in the melt at 0.1 MPa). This results in a strongly non-linear dependence of CO<sub>2</sub> solubility with pressure for melt compositions with SiO<sub>2</sub> contents in the range 18–30 wt.%. At SiO<sub>2</sub> content higher than 30 wt.% the solubility dependence on pressure (from 350 to 0.1 MPa) is linear, as expected in silicate melts for the pressure range considered.

## 5. Discussion

Evidence for a genetic connection between kimberlite and carbonatite magmas goes beyond their, long noticed, spatial and temporal occurrence (e.g. Janse, 1975; White et al., 1995; Mitchell, 2005). Kimberlite and carbonatite melts can both be produced by very low degree partial melting of a carbonated mantle source as inferred from their high concentration of incompatible trace elements (Nelson et al., 1988) and from high pressure melting experiments of carbonated peridotite phase assemblages (Dalton and Presnall, 1998; Gudfinnsson and Presnall, 2005; Dasgupta and Hirschmann, 2006; Ghosh et al., 2009; Rohrbach and Schmidt, 2011). In addition kimberlite and carbonatite melts have been argued to be related by fractionation processes (Dawson and Hawthorne, 1973; Larsen and Rex, 1992; Dalton and Presnall, 1998). This clear link between the two types of magma supports the hypothesis of Brooker et al. (2011) that kimberlite primary magmas were originally more transitional or carbonatitic in composition. The set of transitional synthetic super-liquidus melt compositions that have been produced here should therefore yield a robust approximation of the solubility law for CO<sub>2</sub> in primary kimberlitic melts.

### 5.1. Empirical model of CO<sub>2</sub> solubility in carbonated melts

Based on the solubility experiments presented here and literature data we developed a purely empirical model of CO<sub>2</sub> solubility as a function of the amount of network forming cations (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>) and pressure. We emphasised that it is the first modelling effort addressing such low silica melt compositions. The simple model is defined as a third order polynomial linking the amount of CO<sub>2</sub> dissolved in the melt to the SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> content and in which each coefficient is in turn a function of pressure as follow:

$$CO_{2,wt\%} = A \times (SiO_2 + Al_2O_3)^3 + B \times (SiO_2 + Al_2O_3)^2 + C \times (SiO_2 + Al_2O_3) + D \quad (1)$$

where:

$$A = a \times P^b$$

$$B = c \times P^d$$

$$C = e \times P^f.$$

with  $D$ ,  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $e$  and  $f$  representing adjusted parameters reported in Table 3. The rationale behind the formulation of Eq. (1) is to simulate a pressure-dependent process of dilution from a pure carbonate end-member ( $D = 50$ ) with the addition of network-forming cations (SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>). In order to adjust the parameters in Eq. (1), we used CO<sub>2</sub> solubility data for basalt (Stolper and Holloway, 1988; Matthey, 1991; Pawley et al., 1992; Shishkina et al., 2010), haplo-phonolite (Morizet et al., 2002), phonotephrite (Behrens et al., 2009), and melilitite (Brooker et al., 2001) in addition to selected data from Brey and Ryabchikov (1994), Brooker (1995), Brooker et al. (2011), Brooker and Kjarsgaard (2011), Iacono-Marziano et al. (2012), Morizet et al. (2013), Morizet et al. (2014) and this study (all shown in the

subsequent figures). Eq. (1) reproduces our experimental data well (standard deviation of 0.9 wt.% CO<sub>2</sub> between the modelled and measured values) and allow us to explore a larger P-X(SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>) space. Fig. 4 shows the modelled solubility of CO<sub>2</sub> as a function of pressure for compositions ranging from SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> of 0 to 51 wt.% and pressure from 1500 to 10 MPa. Fig. 4 shows the gradual change in the CO<sub>2</sub> solubility behaviour from carbonate to silicate end-member melts as a function of pressure. We note that from Fig. 4, a typical transitional melt enters the kimberlite “root zone” (see the classical model from Hawthorne, 1975) with a CO<sub>2</sub> content of 10 to 18 wt.%, consistent with the “target value” of 15 wt.% determined by Brooker et al. (2011) for kimberlites.

The range of experiments presented here is not extensive enough to incorporate the effect of temperature and alkali content in Eq. (1). For this, we considered the available from the literature. Fig. 5 compares data from a range of studies and shows the evolution of CO<sub>2</sub> solubility as a function of network forming cations (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>) for a large range of composition and pressure from 2000 to 50 MPa. The predicted evolution from Eq. (1) is also shown for pressure between 2000 and 20 MPa. The melt composition of all data shown in Fig. 5 is reported in Table S2, where one can notice the wide range of compositions explored by these various studies. The variety of methods used to estimate the CO<sub>2</sub> content in these studies (EMP shortfall, Raman, FTIR, elemental analyser and gas chromatography), makes the comparison of dataset not ideal. In addition, while the present study, that of Iacono-Marziano et al. (2012), Morizet et al. (2014), Brooker et al. (2001) and Brey and Ryabchikov (1994) are from super-liquidus experiments, data from Brooker et al. (2011) are from patches of glass in mostly crystallised charges while data from Brooker and Kjarsgaard (2011) and Brooker (1995) are from silicate melts coexisting with an immiscible carbonate melt. Perhaps most importantly, the CO<sub>2</sub>/H<sub>2</sub>O ratio varies widely over the reported dataset with volatile component in experiments from Iacono-Marziano et al. (2012) and Morizet et al. (2014) being dominated by H<sub>2</sub>O. Keeping in mind these limitations in the comparison, we can see that the set of data from Morizet et al. (2014) at 350 and 100 MPa and Morizet et al. (2013) at 1000 MPa are well reproduced by our model. A similar agreement is noted with the data at 2000 MPa from Brooker et al. (2001), at 200 MPa from Brooker et al. (2011) and (to a lesser extent) at 1500 MPa from Brooker (1995). We also note that data at 1000 MPa from Brey and Ryabchikov (1994) (we only report experimental data at 1000 MPa where they reported clear glass) are also well reproduced despite the significant difference in terms of chemical composition (MgO up to 27 wt.%). Fig. 6, shows a plot of experimentally determined vs. calculated CO<sub>2</sub> solubility from which it appears that the highest deviation from the model are for data by Brooker et al. (2011) and Brooker and Kjarsgaard (2011). We made several attempts to link the deviation from the modelled value to the melt composition (Na<sub>2</sub>O, K<sub>2</sub>O, Na<sub>2</sub>O + K<sub>2</sub>O, SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) but could not find any robust correlations. There is however a hint that melt compositions rich in alkali can incorporate more CO<sub>2</sub> than comparatively Ca and Mg-rich compositions (see in Fig. 5 the isolated experiment from Brooker (1995) at 1500 MPa with 15.6 wt.% CO<sub>2</sub> and a composition of 0 wt.% CaO and 37 wt.% Na<sub>2</sub>O). As additional experimental data become available, future models should be able to explore the full effect of composition (in terms of Mg, Ca, Na, K, Fe cations) on CO<sub>2</sub> solubility.

A strong correlation was found between the method used to determine CO<sub>2</sub> content and deviation from our model value. Indeed, 70% of

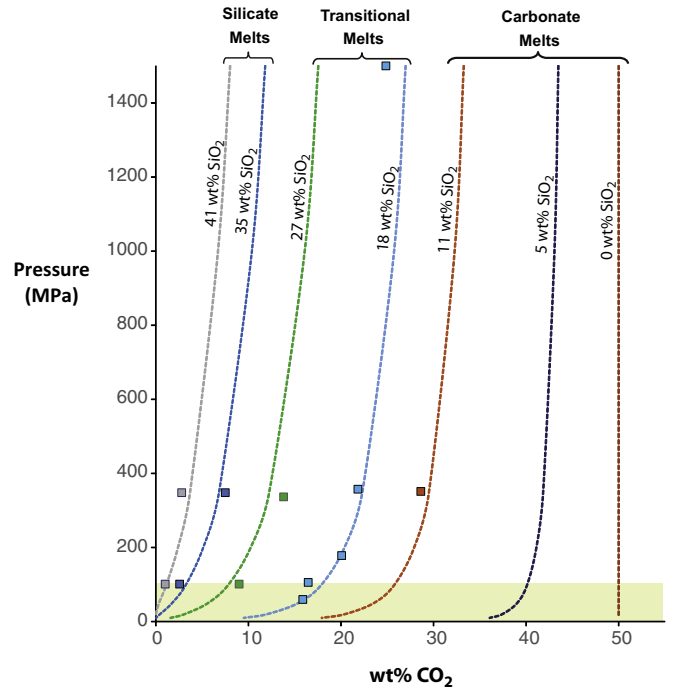


Fig. 4. Modelled evolution of CO<sub>2</sub> solubility as a function of pressure using Eq. (1) for melt compositions ranging from 0 to 41 wt.% SiO<sub>2</sub> and 0 to 51 wt.% SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub>. Experiments of corresponding chemistry are shown as squares of matching colour.

the data located further than two standard deviations away from their calculated value had CO<sub>2</sub> content determined by shortfall of EMPA analyses. Comparing our own EMPA shortfall measurements to CO<sub>2</sub> determined by bulk analyser (Fig. S2), we observe that determining the CO<sub>2</sub> content by EMPA shortfall can lead to an overestimation of 2 to 6 wt.% CO<sub>2</sub>. We therefore conclude (i) that most of the literature data yielding CO<sub>2</sub> solubility values that deviates from our model can be attributed to the large error associated with estimating CO<sub>2</sub> content from EMPA shortfall and (ii) that from the current, limited, dataset there is no identifiable systematic deviations related to the melt composition. Eq. (1) therefore provides a good first order approximation of the CO<sub>2</sub> content of carbonated melt over a large range of composition (SiO<sub>2</sub> < 55 wt.%; Na<sub>2</sub>O + K<sub>2</sub>O < 22 wt.%). The entrapment pressure of recently reported CO<sub>2</sub>-rich melt inclusions from Oldoinyo Lengai (de Moor et al., 2013) for instance, can be estimated using Eq. (1) (yielding an entrapment depth of 265 to 2085 MPa for inclusions containing 3 to 8 wt.% CO<sub>2</sub>).

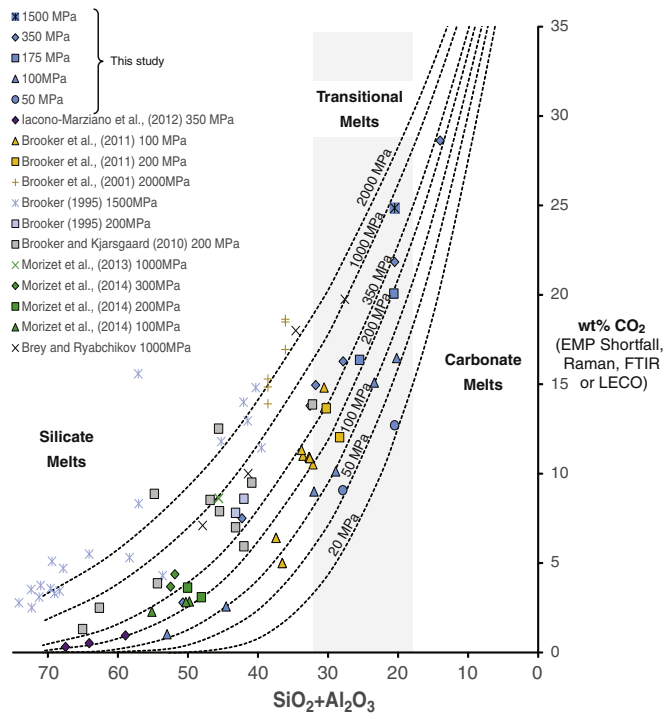
## 5.2. Implications for kimberlite ascent and volcanism

As hypothesised by Brooker et al. (2011) our results indicate that CO<sub>2</sub> solubility decreases with increasing amount of network forming cations over the carbonate–silicate transitional field. This finding supports the conclusions of Russell et al. (2012) that an ascending carbonate melt, assimilating mantle orthopyroxene (OPX) and becoming progressively enriched in silica, will release an increasing amount of CO<sub>2</sub> into the gas phase and promote magma ascent by keeping it buoyant in spite of

Table 3

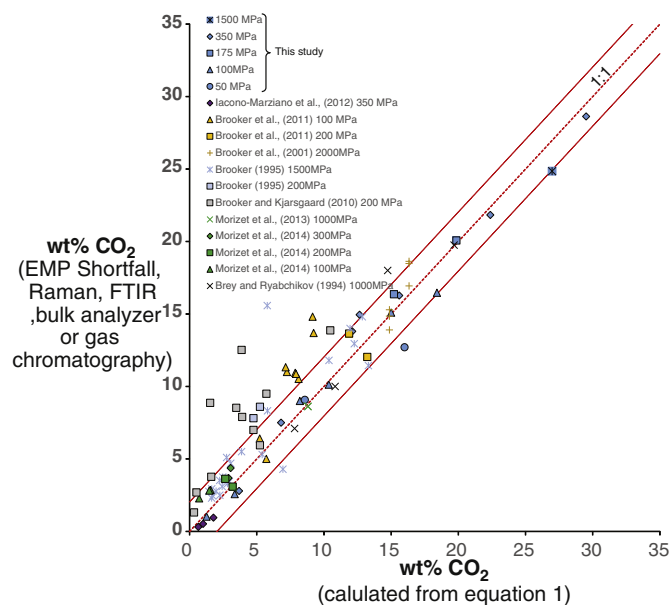
Adjusted parameters (and corresponding standard error on multiple non-linear regression fit) to calculate CO<sub>2</sub> solubility from Eq. (1). Regression was calculated from over 160 data points (detail in text).

	a	b	c	d	e	f	D
Value	−0.001271	−0.476116	0.132494	−0.322187	−4.501117	−0.163249	50
Std. err.	0.000244	0.040612	0.016065	0.020635	0.281876	0.008332	1.4



**Fig. 5.** CO<sub>2</sub> solubility measurements from this study and the literature for compositions across the silicate to carbonate melt transition, equilibrated at 2000, 1500, 350, 200, 100 and 50 MPa. Literature data are from Brooker and Kjarsgaard (2011), Brooker et al. (2011), Iacono-Marziano et al. (2012), Brooker et al. (2001), Brooker (1995), Morizet et al. (2013), Morizet et al. (2014) and Brey and Ryabchikov (1994). Note that literature data are reported using the experiment total pressure and not the  $P_{\text{CO}_2}$ . Model prediction values from Eq. (1) are shown for a range of pressure (2000 to 20 MPa) as dotted black curves.

increasing xenocryst loading. The effect of pressure (shown in Figs. 3 and 4) on transitional melts appears to be a function of their composition; melts with a composition closer to the carbonate end-member retain a large quantity of CO<sub>2</sub> until very shallow (3 km) depth while slightly



**Fig. 6.** Experimentally determined vs. calculated CO<sub>2</sub> solubility using Eq. (1). Dotted red line represents the 1:1 line while continuous red lines on either sides represent the  $\pm 2\sigma$  deviation.

more silicate-rich melts show a continuous and progressive degassing profile with CO<sub>2</sub> being equally released from mantle depth to the surface. The solubility–pressure relationships shown by the transitional melt compositions in Figs. 3 and 4 are intermediate between the behaviour of a carbonate melt which will show little pressure dependence on solubility, and that of a typical silicate melt which will show a mostly linear relationship in the pressure range considered (Figs. 3, 4, e.g. Papale et al., 2006; Iacono-Marziano et al., 2012).

The behaviour of transitional melts, retaining more than 18 wt.% CO<sub>2</sub> up until very shallow depth should lead to a rapid increase in ascent velocity while reaching the last 3 km depth where important quantities of CO<sub>2</sub> will be released (Fig. 4). This acceleration will be exacerbated by the fact that the volume fraction of gas will reach values higher than 77%, corresponding to the point at which the bubble foam will collapse (Woods, 1995) changing the continuous phase from a bubbly liquid magma to an ash-laden gas and therefore considerably increasing the flow speed as the frictional force become much smaller and the viscosity becomes closer to that of the gas phase. This ascent scenario can readily explain some of the typical morphological features of kimberlite pipes. (i) The widening upward geometry of the pipe, typical of eruptions happening at depth, can be explained by the high amount of CO<sub>2</sub> released over a, most probably, very small time increment leading to overpressure and explosion below the surface. (ii) The appearance of breccias and irregularly shaped blocks at depth of ~3 km, in the “root zone” (see the classical model from Hawthorne, 1975) is consistent with large amount of CO<sub>2</sub> starting to be released at this depth and the associated rapid volumetric expansion (Fig. 4). The occurrence of hypabyssal intrusions of kimberlites however suggests that some kimberlite stall during their ascent through the crust. Although we cannot confidently assign a reason for this, possibilities include the loss of volatiles, segregating from the magma during ascent or the progressive cooling of the magma (Kavanagh and Sparks, 2009); both processes inducing crystallisation and greatly increasing magma viscosity. Experiments on these compositions suggest that crystallisation is extremely rapid, as illustrated by the speed at which quench crystals formed in some of our experiments.

While CO<sub>2</sub> is the most abundant volatile in kimberlite magmas, an unknown but probably significant amount of water is also dissolved in these melts (up to 10 wt.%; Kopylova et al., 2007; also see discussion in Sparks et al., 2009 and experimental investigation by Keppler, 2003). Water degassing is therefore likely to exert a large influence on the ascent dynamics of Kimberlite melts. It remains unclear however whether this process would enhance, limit or displace the depth at which the CO<sub>2</sub>-exsolution-triggered acceleration of kimberlite melts that we predict takes place.

## 6. Conclusions

We have determined CO<sub>2</sub> solubility laws for kimberlite melt and have also provided a general solubility model for carbonated melt composition ( $\text{SiO}_2 < 55 \text{ wt.}\%$ ) at pressure between 50 and 1500 MPa. We found that (i) CO<sub>2</sub> solubility decreases steadily with increasing amount of network forming cations (ii) The effect of pressure on CO<sub>2</sub> solubility is a strong function of composition with low SiO<sub>2</sub> melts retaining large amount (~15 wt.%) of CO<sub>2</sub> up to very shallow pressure (~100 MPa) while more silicated melts have a near linear CO<sub>2</sub> solubility dependence on pressure. We propose that this peculiar pressure–solubility dependency should result in a strong acceleration of an ascending kimberlite magma in the last 3 km of crust where CO<sub>2</sub> starts to exsolve in large quantities. This behaviour can explain morphological features of kimberlite pipes, notably the depth extent of the root zone and the widening-upward shape of the conduit and can account for the highly explosive character of Kimberlite eruptions.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.chemgeo.2014.11.017>.

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