Deep sourced fluids for peridotite carbonation in the shallow mantle wedge of a fossil subduction zone: Sr and C isotope profiles of OmanDP Hole BT1B

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Abstract

Completely carbonated peridotites represent a window to study reactions of carbon-rich fluids with mantle rocks. Here we present details on the carbonation history of listvenites close to the basal thrust in the Samail ophiolite. We use samples from Oman Drilling Project Hole BT1B, which provides a continuous record of lithologic transitions, as well as outcrop samples from listvenites, metasediments and metamafics below the basal thrust of the ophiolite. $^{87}Sr/^{86}Sr$ of listvenites and serpentinites, ranging from 0.7090 to 0.7145, are significantly more radiogenic than mantle values, Cretaceous seawater, and other peridotite hosted carbonates in Oman. $\delta^{13}C$ in the listvenites and serpentinites range from -10.6carbon component with $\delta^{13}C$ as low as -27reaffirms the presence of carbonaceous material in Hole BT1B. The source of the radiogenic Sr was probably similar to Hawasina metasediments that underlie the ophiolite, with values up to 0.7241 in clastic lithologies. These results indicate that decarbonation reactions in such clastic sediments, during subduction at temperatures above 500°C, form carbon rich fluids that could have migrated updip, supplying radiogenic $^{87}Sr/^{86}Sr$ and fractionated $\delta^{13}C$ to BT1B serpentinites and listvenites.

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Key Points:

- Strontium and Carbon were added to the peridotites during alteration of mantle peridotite with carbonated fluid derived from decarbonation reaction.

Abstract

Completely carbonated peridotites represent a window to study reactions of carbon-rich fluids with mantle rocks. Here we present details on the carbonation history of listvenites close to the basal thrust in the Samail ophiolite. We use samples from Oman Drilling Project Hole BT1B, which provides a continuous record of lithologic transitions, as well as outcrop samples from listvenites, metasediments and metamafics below the basal thrust of the ophiolite. $^{87}Sr/^{86}Sr$ of listvenites and serpentinites, ranging from 0.7090 to 0.7145, are significantly more radiogenic than mantle values, Cretaceous seawater, and other peridotite hosted carbonates in Oman. The Hawasina metasediments that underlie the ophiolite, on the other hand, show higher $^{87}Sr/^{86}Sr$ values of up to 0.7241. $\delta^{13}C$ values of total carbon in the listvenites and serpentinites range from -10.6‰ to 1.92‰. We also identified a small organic carbon component with $\delta^{13}C$ as low as -27‰. Based on these results, we propose that during subduction at temperatures above 500°C, carbon-rich fluids derived from decarbonation of the underlying sediments migrated up dip and generated the radiogenic $^{87}Sr/^{86}Sr$ signature and the fractionated $\delta^{13}C$ values of the serpentinites and listvenites in core BT1B.

Plain Language Summary

Samples from Oman Drilling Project Hole BT1B provide a record of interactions of fluids rich in carbon dioxide with mantle rocks. This interactions lead to the formation of listvenites, rocks composed mainly by magnesite and quartz. Here we describe the formation of listvenites in the Oman ophiolite using Strontium and Carbon isotopes to characterize the source and nature of the fluid that pervasively transform the mantle rocks that now store vast amounts of carbon dioxide.

1 Introduction

Hydration and carbonation of ultramafic rocks are important processes in the carbon and water cycle of our planet (Alt et al., 2013; Fruh-Green et al., 2004). These alteration reactions are sinks of water and carbon where peridotites are exposed on the seafloor forming alteration minerals like serpentine and carbonates (Alt et al., 2013; Klein et al., 2020; Macdonald & Fyfe, 1985; Paulick et al., 2006) which are carried back into the mantle in convergent margins. Fluids derived from the subducted slab can migrate and interact with the mantle wedge in subduction zones, so that the “leading edge of the mantle wedge” aka the “cold nose”, can be partially hydrated and carbonated (Blakely et al., 2005; Hyndman & Peacock, 2003; Peter B. Kelemen & Manning, 2015). This is usually inferred from seismic data (e.g. DeShon and Schwartz, 2004; Kamiya and Kobayashi, 2000; Tibi et al., 2008; Tsuji et al., 2008). Understanding the interaction of carbon-bearing hydrous fluids with peridotites is important to supplement and constrain geophysical observations.

Fully carbonated peridotites, also known as listvenites, provide a window into the alteration processes that occur in the “cold nose” of the mantle wedge above subduction zones, where mantle peridotite reacts with hydrous and carbonated fluids likely derived from the subducting slab at moderate temperatures and pressures (Beinlich et al., 2012; Boskabadi et al., 2017, 2020; Falk & Kelemen, 2015; Manuel D. Menzel et al., 2018). Formation of listvenites appears to be restricted to particular conditions requiring high carbon concentrations in the fluid

(Falk & Kelemen, 2015; Hansen et al., 2005; Peter B. Kelemen et al., 2021; Manuel D. Menzel et al., 2018). For example, complete carbonation of peridotites to form listvenites is not observed near the surface in ophiolites (e.g. Clark and Fontes, 1990; de Obeso and Kelemen, 2020, 2018; Garcia del Real et al., 2016; Kelemen and Matter, 2008; Noël et al., 2018; Quesnel et al., 2016; Schwarzenbach et al., 2016). It is also not observed near the seafloor, where serpentinization and formation of carbonate veins are common (e.g Bach et al., 2011; Delacour et al., 2008; Schwarzenbach et al., 2013). Fluid sources for complete carbonation have been associated with subduction in different listvenite localities. Menzel at al. (2018) attributed carbonation of harzburgite in the Advocate ophiolite (Canada) to fluxing by slab-derived, CO_2-rich fluids. Isotopic data ($\delta^{13}C$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$) of listvenites in the Late Cretaceous ophiolites of eastern Iran point to carbon-bearing fluids derived from subducted sedimentary units as the source of carbon (Boskabadi et al., 2020).

In Oman, listvenites occur along the basal thrust of the ophiolite (Nasir et al., 2007; Wilde et al., 2002). Previous studies have investigated their formation conditions and the nature of the carbonation fluids without reaching conclusive answers on the source of the fluids (Beinlich et al., 2020; Falk & Kelemen, 2015; Nasir et al., 2007; Stanger, 1985). In this paper, we present $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ data on samples from Oman Drilling Project Hole BT1B and the underlying sediments of the Hawasina Formation. We show that devolatization of the subducting sediments similar to the Hawasina Formation likely generated the carbonation fluids which reacted with the mantle wedge in this fossil subduction zone to form listvenites. These processes probably operate in subduction zones worldwide, where fluids migrate updip along the slab mantle interface, and then react with hanging wall peridotites. Our results have implications for the global carbon cycle, as significant amounts of carbon could be stored in the mantle during mantle wedge carbonation.

2 Geological setting

2.1 The Samail ophiolite

The Samail ophiolite, along the northeast coast of Oman and the United Arab Emirates (UAE), is the best-exposed block of oceanic crust and its underlying mantle in the world. It was thrust over adjacent oceanic lithosphere soon after magmatic formation, and then onto the margin of the Arabian subcontinent in the late Cretaceous. The mantle section of the ophiolite is mainly composed of highly depleted, residual mantle peridotites (mostly harzburgites, e.g. (Godard et al., 2000; Hanghøj et al., 2010; Monnier et al., 2006), together with 5 to 15% dunite (Braun, 2004; Braun & Kelemen, 2002; Collier, 2012). Near the basal thrust, interlayered dunites and refertilized harzburgites comprise the distinctive “Banded Unit” (Khedr et al., 2014). The peridotites are pervasively serpentinized, with serpentine (± brucite) making up ~ 30-100 wt% of “fresh” rock (Godard et al., 2000; Hanghøj et al., 2010; Monnier et al., 2006) and/or completely carbonated to form listvenites (Falk & Kelemen, 2015; Nasir et al., 2007; Stanger, 1985; Wilde et al., 2002). The listvenites only occur within a few km of the basal thrust of the ophiolite, and within the tectonic melanges with a serpentine matrix just below the base of the ophiolite (Nasir et al., 2007; Stanger, 1985).

2.2 Lithologies below the Samail ophiolite nappe

Beneath the mantle section of the Samail ophiolite is a locally preserved "metamorphic sole". This sole is exposed discontinuously along the basal thrust, juxtaposed with the overlying Banded Unit at the base of the Samail mantle section. It records peak metamorphic temperatures of 700-900°C and imprecise peak pressures of 0.8 to 1.4 GPa (Cowan et al., 2014; Hacker & Mosenfelder, 1996; M. P. Searle & Malpas, 1980; Michael P. Searle & Cox, 2002; Soret et al., 2017). A lower temperature unit (~450-550°C) with similar peak pressures (0.8 to 1.2 GPa) has also been identified from the metamorphic section of Oman DP Hole BT1B (Kotowski et al., 2021). The base of the sole is in fault contact with low grade allochthonous sediments of the Hawasina formation, which is composed of pelagic clastic units interlayered with limestones (Bechennec et al., 1990; Béchennec et al., 1988) deposited from the late Permian to the Cretaceous. The Hawasina sedimentary units were thrusted over autochthonous Mesozoic to Proterozoic platform sediments of the Arabian continental margin, forming nappes between the autochton and the ophiolite.

2.3 *OmanDP Hole BT1B and Oman Listvenites*

Hole BT1B was drilled in March 2017 in Wadi Mansah (23.364374°N, 58.182693°E), which yielded a total length of 300.1 m with 100% recovery (Kelemen et al., 2020). The upper 6 meters are composed of alluvial gravels followed by an ultramafic sequence comprised of listvenites (carbonated peridotites) interlayered with two serpentinite bands (80-100 m depth and 181 to 186 m depth). A thick (0.42 m) layer of grey-green fault gouge at 196.6 m–197.1 m depth separates the ultramafic units from the metamorphic sole composed of fine-grained metasediments and metabasalts (Kelemen et al., 2021; Kelemen et al., 2020). To the first order, alteration of peridotite to form serpentinite and listvenite in Hole BT1B was nearly isochemical except for the addition of H_2O and CO_2. Average bulk rock Mg/Si, Fe/Si, Al/Si, Fe/Mg, and Cr/Al ratios in serpentinite and listvenite are close to the average composition of the Samail peridotite (Kelemen et al. 2020, Kelemen et al. 2021) and similar to the composition of previously studied listvenites from the outcrops extending north and northeast from the drill site (Falk & Kelemen, 2015). The core provides a unique record of the interaction between peridotite in the leading edge of the mantle wedge and hydrous, CO_2-rich fluids derived from subducted lithologies. For an expanded version of the geology of Oman DP Hole BT1B and MoD mountain we refer the reader to the Proceedings of the Oman Drilling Project (Kelemen et al., 2020) and Kelemen et al. (2021) in this Special Issue.

3 Materials and Methods

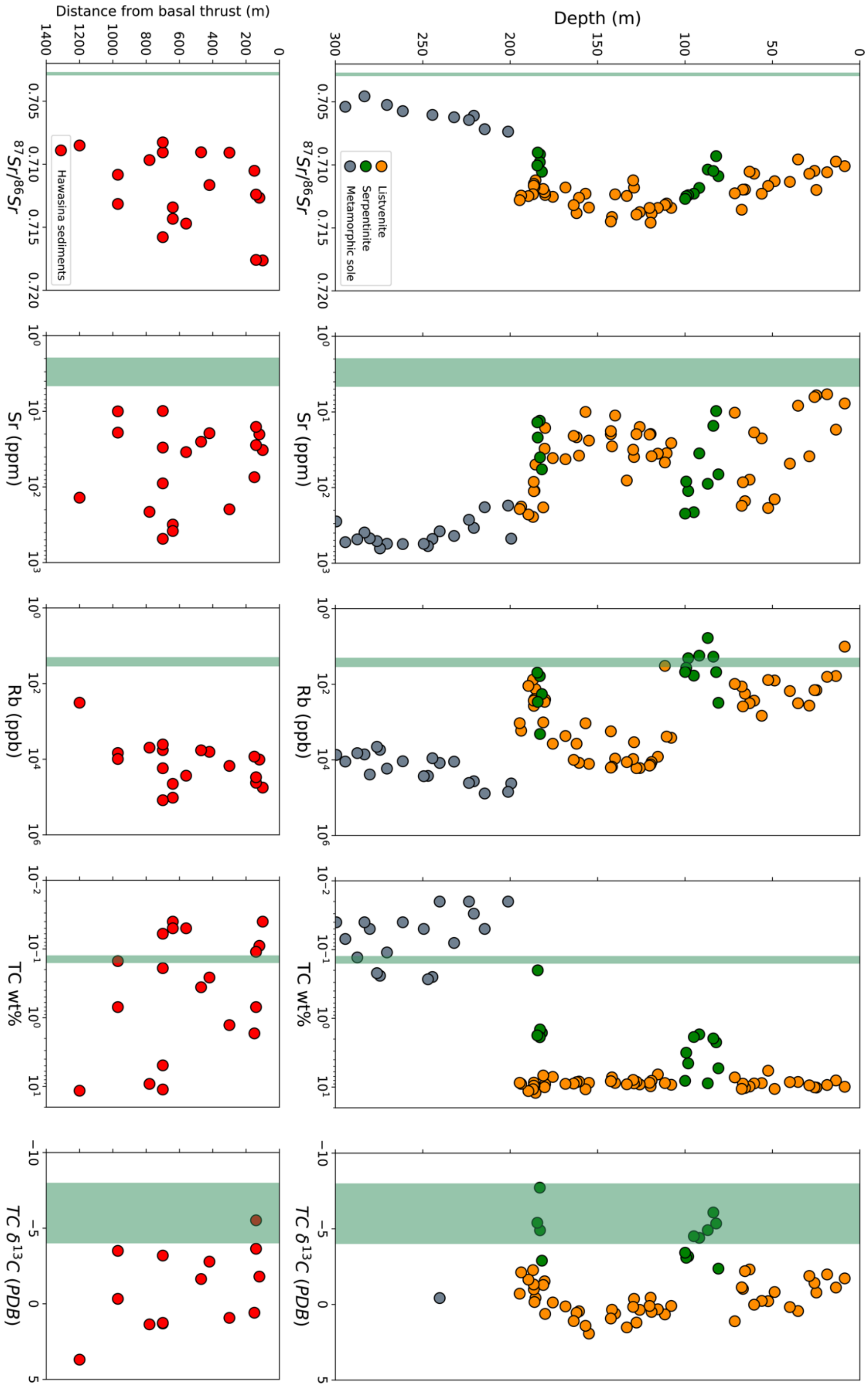
Samples analyzed for this study comprise a suite of drill core samples from OmanDP Hole BT1B and hand samples of the Hawasina formation. Drill core samples encompass all the identified lithologies from Hole BT1B. Major element compositions for Hole BT1B samples were reported in the *Proceedings of the Oman Drilling Project* (Kelemen et al 2020) with the exception of samples in the 181-186m depth interval which are reported by Godard et al. Trace element compositions of Hole BT1B samples can be found in Godard et al. Trace element compositions and loss on ignition for Hawasina formation outcrop samples were analyzed at Lamont Doherty Earth Observatory (LDEO). Rb and Sr concentrations were analyzed using a VG PlasmaQuad ExCell quadrupole ICP-MS following HNO_3-HF digestion. Major element compositions of the Hawasina samples are available in supplementary table 1. Additional Sr isotopes were measured on samples from outcrops northeast of Hole BT1B (Falk & Kelemen 2015).

For Sr isotope analysis, bulk rock powder was fully digested in a HNO_3-HF mixture overnight and redissolved in 3N HNO_3 prior to column chemistry using the Eichrom® Sr resin. Purified Sr were analyzed for isotopic compositions interspersed with US National Institute of Standards and Technology (NIST) SRM 987 on a Thermo Scientific Neptune multi-collector ICP-MS at LDEO. In-run mass fractionations were normalized to $^{86}Sr/^{88}Sr=0.1194$. Unknowns were normalized to SRM 987 $^{87}Sr/^{86}Sr$ value of 0.701248. International standards BHVO-2 yielded $^{87}Sr/^{86}Sr$ value of 0.703509±41 (2σ, n = 3) and BCR-2 yielded 0.705046±34 (2σ, n = 3), which agree with published values from Weis et al. (2006).

Total Carbon (TC) was measured from the same bulk rock powder splits as for Strontium isotopes. Total Organic Carbon (TOC, or reduced carbon) was measured from the residual rock powder after the removal of Inorganic Carbon (carbonate carbon) through reaction with dilute (3 N) HCl for at least 3 days, followed by washing with Millipore® water. Concentrations and $\delta^{13}C$ ratios of total carbon (TC) and total organic carbon (TOC), were determined using a Costech element analyzer coupled with a Thermo Scientific Delta V plus mass spectrometer at LDEO. Sample runs were calibrated using Acetanilide for carbon contents ($R^2=0.9998$). For $\delta^{13}C$ we used USGS40 ($\delta^{13}C$ =-26.77±0.16‰ V-PDB, n=4), USGS41 ($\delta^{13}C$ =37.63±0.12‰ V-PDB, n=4) and USGS24 ($\delta^{13}C$ =-16.04±0.13‰ V-PDB, n=4). All measured values of $\delta^{13}C$ standards agree with accepted values reported by the United States Geological Survey (USGS). Inorganic carbon contents and $\delta^{13}C$ of TIC were estimated by mass balance between TC and TOC.

3 Results

Depth profiles of $^{87}Sr/^{86}Sr$, Sr and Rb concentrations, carbon concentrations, Total Carbon and Total carbon $\delta^{13}C$ are shown in Figure 1 and Table 1 and 2. The Hawasina sediments are plotted with respect to map distance to the closest metamorphic sole/ultramafic contact.



Depth (m)
Distance from basal thrust (m)
Listvenite
Serpentinite
Metamorphic sole
Hawasina sediments
$^{87}Sr/^{86}Sr$
Sr (ppm)
Rb (ppb)
TC wt%
TC $\delta^{13}C$ (PDB)

Figure 1. Depth profiles of OmanDP Hole BT1B and distance from basal thrust for Hawasina sediments. From left to right $^{87}Sr/^{86}Sr$ (measured), Sr concentrations, Rb concentrations, total carbon (TC) concentration, total carbon $\delta^{13}C$. Green bands for reference from left to right are average MORB $^{87}Sr/^{86}Sr$ (measured) (Gale et al., 2013; Hofmann, 2013), Oman harzburgite average Sr (ppm) and Rb (ppb) (Godard et al., 2000; Hanghøj et al., 2010; Monnier et al., 2006), Oman harzburgite average total carbon (TC) (Peter B. Kelemen & Manning, 2015), average mantle $\delta^{13}C$ (Deines, 2002). The distance from the basal thrust for the Hawasina sediments (bottom panels) is measured as the horizontal distance to the closest mapped metamorphic sole/ultramafic contact.

Sample	Depth CCD (m)	Lithology	87Sr/86Sr	2SE total error	Rb (ppb)	Sr (ppb)	TC (wt%)	TC d13C (‰PDB)	OC (wt%)	TOC (d13C ‰PDB)
C5704B_7Z4_14-19	8.64	listvenite	0.7101029	0.000023	10	7733	9.9	-1.72	NA	NA
C5704B_9Z3_23-28	13.67	listvenite	0.7097414	0.000022	61	17156	8.01	-1.12	NA	NA
C5704B_12Z1_84-89	18.72	listvenite	0.7105864	0.000023	64	5844	9.32	-1.98	NA	NA
C5704B_14Z2_25-30	24.86	listvenite	0.7119908	0.000023	144	6042	10.16	-0.79	0.04	-14.58
C5704B_14Z3_71-76	25.93	listvenite	0.710479	0.000019	143	6351	10.08	-1.42	1.48	-2.88
C5704B_16Z3_7-12	28.9	listvenite	0.7107064	0.000021	368	38660	9.42	-1.88	NA	NA
C5704B_18Z3_25-31	35.34	listvenite	0.7095716	0.000023	319	8284	8.42	0.44	1.49	NA
C5704B_20Z1_78-83	40.01	listvenite	0.7113509	0.000022	152	48281	8.46	0.18	NA	NA
C5704B_23Z1_37-42	48.75	listvenite	0.711299	0.000019	80	142571	10.63	-0.82	0.07	-19.07
C5704B_25Z2_55-60	52.45	listvenite	0.7116712	0.000020	78	186366	5.78	-0.21	0.02	-17.36
C5704B_26Z2_77-82	56.11	listvenite	0.7122875	0.000019	682	22385	8.76	-0.23	NA	NA
C5704B_28Z1_69-74	60.47	listvenite	0.7106974	0.000020	272	18688	8.86	0.02	0.09	-13.68
C5704B_30Z2_53-58	63.07	listvenite	0.7105413	0.000021	318	78656	9.82	-2.31	NA	NA
C5704B_31Z3_31-37	65.71	listvenite	0.7119567	0.000019	178	151322	10.3	-2.20	0.22	-6.87
C5704B_32Z1_19-24	66.87	listvenite	0.7119635	0.000020	386	85105	8.92	-1.03	0.88	-4.52
C5704B_32Z2_7-12	67.55	listvenite	0.7135589	0.000019	115	174106	10.61	-1.13	2.43	NA
C5704B_35Z1_6-11	71.54	listvenite	0.7122553	0.000022	98	10237	7.23	1.11	0.89	NA
C5704B_38Z3_86-91	80.9	serpentinite	0.7108931	0.000022	310	66812	5.33	-2.37	0.09	-10.07
C5704B_39Z1_25-30	82.18	serpentinite	0.709307	0.000022	48	9733	2.23	-5.35	0.10	-13.67
C5704B_39Z3_13-8	83.81	serpentinite	0.7104894	0.000021	19	15271	1.96	-6.08	0.03	-22.04
C5704B_40Z3_3-8	86.98	serpentinite	0.710374	0.000019	6	89171	8.81	-4.91	0.06	-24.23
C5704B_42Z2_26-31	91.85	serpentinite	0.7118308	0.000021	18	35313	1.71	-4.40	0.07	NA
C5704B_43Z2_3-8	94.96	serpentinite	0.712288	0.000019	59	211715	1.87	-4.51	0.07	NA
C5704B_44Z2_29-34	98.17	serpentinite	0.7124092	0.000019	21	110987	4.52	-3.17	0.04	-15.24

C5704B_44Z3_57-62	99.31	serpentinite	0.7124888	0.000023	37	83218	3.16	-3.08	0.06	-26.45
C5704B_44Z4_50-55	99.94	serpentinite	0.7127018	0.000020	47	221049	8.11	-3.42	0.29	-4.90
C5704B_47Z3_18-23	107.88	listvenite	0.7134127	0.000020	2612	25806	9.26	0.10	0.05	-23.97
C5704B_48Z2_26-31	110.52	listvenite	0.7130681	0.000022	2429	35139	NA	NA	0.02	-25.40
C5704B_48Z3_90-95	111.5	listvenite	0.7131781	0.000023	33	46533	8.74	0.66	NA	NA
C5704B_50Z4_65-70	115.53	listvenite	0.7134198	0.000023	8287	35574	6.55	0.32	NA	NA
C5704B_52Z1_60-65	119.13	listvenite	0.7138657	0.000019	11406	38542	8.1	0.49	0.44	-5.64
C5704B_52Z3_0-5	119.67	listvenite	0.7145867	0.000022	13213	19572	9.72	-0.44	NA	NA
C5704B_52Z3_61-66	120.28	listvenite	0.7134184	0.000019	14220	19930	8.64	0.10	NA	NA
C5704B_54Z2_47-52	125.92	listvenite	0.7137525	0.000022	16514	15830	9.15	0.36	NA	NA
C5704B_55Z1_8-13	127.76	listvenite	0.7139473	0.000022	16596	19674	8.37	1.20	0.07	NA
C5704B_55Z2_59-64	129.16	listvenite	0.7118074	0.000020	3417	39477	8.84	-0.37	0.11	-4.23
C5704B_55Z3_15-20	129.65	listvenite	0.7112276	0.000022	9522	31563	7.87	0.16	NA	NA
C5704B_56Z4_11-16	133.29	listvenite	0.7124671	0.000022	11464	80713	9.11	1.52	NA	NA
C5704B_60Z1_12-17	140	listvenite	0.7123404	0.000022	9275	11158	8.69	0.61	NA	NA
C5704B_60Z3_40-45	141.79	listvenite	0.7141358	0.000019	15152	28514	7.22	0.35	0.31	0.74
C5704B_60Z4_24-29H	142.43	listvenite	0.7144926	0.000020	16037	19667	8.21	0.93	NA	NA
C5704B_64Z4_18-23	154.95	listvenite	0.7133899	0.000020	12775	23908	8.68	1.93	NA	NA
C5704B_65Z3_33-38	156.91	listvenite	0.7122888	0.000020	1079	10005	10.76	1.41	0.10	-16.35
C5704B_66Z3_66-71	160.62	listvenite	0.7126074	0.000022	11964	37852	8.31	0.45	0.06	-24.15
C5704B_67Z2_26-31	162.03	listvenite	0.7138291	0.000022	3747	21596	8.48	0.55	NA	NA
C5704B_67Z4_39-44	163.67	listvenite	0.7131952	0.000019	10001	20778	8.89	1.10	0.04	-10.87
C5704B_69Z2_55-63	168.38	listvenite	0.7117951	0.000023	2341	42165	8.98	0.13	NA	NA
C5704B_71Z4_0-8	175.63	listvenite	0.7125344	0.000018	3745	40763	7.12	-0.13	0.05	-16.71
73-1-71.0-75.0cm	180.01	listvenite	0.7123924	0.000022	254	16269	9.1	0.63	0.24	-4.63
C5704B_73Z2_0-5	180.3	listvenite	0.71218	0.000020	292	30626	10.04	-1.53	0.21	-8.61
73-3-8.0-13.0cm	181.1	listvenite	0.7119166	0.000022	1021	182886	6.79	-1.29	0.02	-14.10
73-4-11.0-16.0cm	181.85	serpentinite	0.7105479	0.000022	182	57427	1.62	-2.89	0.04	-16.58
C5704B_74Z1_56-64	182.95	serpentinite	0.7091689	0.000023	2073	39906	1.45	-4.90	0.05	-27.04
74-2-0.0-5.0cm	183.07	serpentinite	0.7097785	0.000017	61	13067	1.88	-7.72	0.07	-10.96
74-3-42.0-47.0cm	184.24	serpentinite	0.7090228	0.000019	294	21788	0.2	-10.62	0.04	-24.59
74-3-67.0-73.0cm	184.49	serpentinite	0.7100467	0.000023	49	13717	1.77	-5.40	0.24	-9.94
75-1-12.0-16.0cm	185.52	listvenite	0.7112295	0.000022	134	49603	12.12	-0.43	0.10	-17.53
75-1-70.0-75.0cm	186.1	listvenite	0.7117597	0.000020	247	110258	9.7	-0.16	0.16	NA

75-2-27.0-32.0cm	186.46	listvenite	0.7115092	0.000022	373	111620	8.61	-1.00	0.07	NA
C5704B_75Z2_31-40	186.54	listvenite	0.7116533	0.000021	272	84029	9.54	-1.32	0.11	-11.87
75-2-76.0-82.0cm	186.95	listvenite	0.7123277	0.000019	76	244293	10.73	-2.27	0.69	NA
C5704B_76Z2_38-42	189.58	listvenite	0.7124782	0.000019	111	227322	11.43	-1.64	0.33	-12.42
C5704B_77Z3_40-48	193.71	listvenite	0.7124411	0.000019	1696	178429	8.98	-2.12	0.26	-5.61
C5704B_77Z4_43-48	194.57	listvenite	0.7127999	0.000020	1072	192155	8.66	-0.71	0.17	-9.16
C5704B_82Z1_50-55	201.18	Metamorphic	0.7073636	0.000020	70152	173001	0.02	NA	NA	NA
C5704B_88Z2_76-82	214.59	Metamorphic	0.7071713	0.000018	77502	182069	0.05	NA	NA	NA
C5704B_90Z3_8-13	220.79	Metamorphic	0.7061036	0.000019	36796	341585	0.03	NA	NA	NA
C5704B_92Z3_0-8	223.58	Metamorphic	0.7064436	0.000020	40839	266694	0.02	NA	NA	NA
C5704B_96Z2_0-8	232.1	Metamorphic	0.7062253	0.000019	11143	436010	NA	NA	0.09	-19.25
C5704B_99Z1_0-5	240.33	Metamorphic	NA	NA	12063	378913	0.02	-0.42	NA	NA
C5704B_100Z2_13-21	244.47	Metamorphic	0.7060383	0.000018	9065	477887	0.25	NA	NA	NA
C5704B_105Z4_31-36	261.44	Metamorphic	0.705739	0.000019	10901	558612	0.04	NA	NA	NA
C5704B_109Z4_24-32	270.5	Metamorphic	0.7052469	0.000020	17054	553129	0.11	NA	NA	NA
C5704B_116Z1_31-39	283.35	Metamorphic	0.7045642	0.000019	7182	392644	0.04	NA	NA	NA
C5704B_124Z1_53-61	294.32	Metamorphic	0.7053928	0.000018	11092	527027	0.07	NA	NA	NA

Table 1. OmanDP Hole BT1B Strontium and Carbon concentrations and isotope rations

Sample	Latitude	Longitude	Elevation (m)	Distance from Basal thrust (m)	Sr (ppm)	Rb (ppm)	87Sr/86Sr	2SE total error	C (wt%)	d13C (‰ PDB)
OM20-01	23.3727	58.18973	556	NA	360.92	3.6	0.7093033	0.000008	0.99	-0.61
OM20-03	23.35872	58.23122	364	420	19.47	6.38	0.7116514	0.00001	0.26	-2.79
OM20-05	23.37326	58.51663	468	470	25.23	5.8	0.7090506	0.000007	0.36	-1.64
OM20-06	23.3763	58.21493	493	640	314.26	44.7	0.7134211	0.000007	0.04	NA
OM20-07	23.37628	58.21508	488	640	382.46	103.96	0.7143305	0.000007	0.05	NA
OM20-08	23.35756	58.21843	418	120	20.15	10.2	0.7126578	0.000007	0.09	-1.8
OM20-09	23.35744	58.21829	432	100	32.54	56.28	0.7176305	0.000006	0.04	NA
OM20-11	23.35789	58.21856	454	140	16.06	41.9	0.7175916	0.00001	0.11	-5.52
OM20-12	23.38609	58.14561	262	780	213.39	4.94	0.7096678	0.000009	9.18	1.36
OM20-13	23.39792	58.18225	278	150	74.29	8.52	0.7105193	0.000006	1.69	0.59
OM20-14	23.40735	58.15496	269	700	9.9	17.3	0.7157845	0.000008	0.19	-3.19
OM20-15	23.40758	58.1547	265	700	89.69	5.73	0.7090595	0.000009	4.93	1.3

OM20-16	23.39377	58.17862	302	560	34.61	27.25	0.7147076	0.000006	0.05	NA
OM20-17	23.40754	58.1546	273	700	30.13	121.1	0.7241322	0.000009	0.06	NA
OM20-10	23.35786	58.21854	458	140	27.97	29.92	0.712403	0.000007	0.7	-3.64
OM20-18	23.40763	58.15468	275	700	484.97	4.07	0.7082638	0.000009	11.06	1.26
OM20-19	23.39655	58.04998	310	300	197.35	15.03	0.7090828	0.000007	1.28	0.93
OM20-42	23.414996	58.161405	253	1200	138.71	0.32	0.7085112	0.00001	11.53	3.69
OM20-04a	23.36214	58.23478	384	970	19.13	6.84	0.7108331	0.000009	0.7	-0.33
OM20-04B	23.36214	58.23478	384	970	10.01	9.86	0.71315	0.000008	0.15	-3.5

Table 2. Hawasina metasediments Strontium and Carbon concentrations and isotope rations

3.1 Strontium Isotopes

Measured $^{87}Sr/^{86}Sr$ values in Oman DP Hole BT1B lithologies show clear differences between (a) the metamorphic sole and (b) the listvenites and serpentinites. The listvenites and serpentinites vary from a minimum value of 0.709 in the upper serpentinite band to a maximum of 0.715 in some listvenites. $^{87}Sr/^{86}Sr$ values in the listvenites increase with depth from the surface to 150 m while the serpentinite band between 80-100 m have lower values. Below 150 m, $^{87}Sr/^{86}Sr$ values are relatively constant with increasing depth, until the second serpentine band at 181-186 m. Below the basal thrust, $^{87}Sr/^{86}Sr$ values are significantly lower in the metamorphic sole from 0.704 to 0.706, followed by lower $^{87}Sr/^{86}Sr$ values with greater depths. Although the metamorphic sole contains meta-basalts and what appear to be volcanoclastic sediments (Boudier et al., 1988; Kotowski et al., 2021; M. P. Searle & Malpas, 1980, 1982), all of the samples have higher $^{87}Sr/^{86}Sr$ than typical mid-ocean ridge basalts (MORB) (Gale et al., 2013; Hofmann, 2013). The Sr isotope values of the listvenite and serpentinite samples from BT1B are similar to those of listvenites in nearby outcrops (Falk and Kelemen, 2015, Figure 2), which are significantly more radiogenic than $^{87}Sr/^{86}Sr$ values of Oman peridotites (Gerbert-Gaillard, 2002; Lanphere et al., 1981; McCulloch et al., 1981) and Cretaceous to modern seawater (McArthur et al. 2001), but less radiogenic than some Hawasina and autochthonous sediments (Weyhenmeyer, 2000). Our samples of the Hawasina sediments, and those collected from the same region by

Falk and Kelemen (2015) have $^{87}Sr/^{86}Sr$ values ranging from 0.7082 to 0.7241. Six of these Hawasina samples are more radiogenic than any of the samples from Hole BT1B (Figure 2).

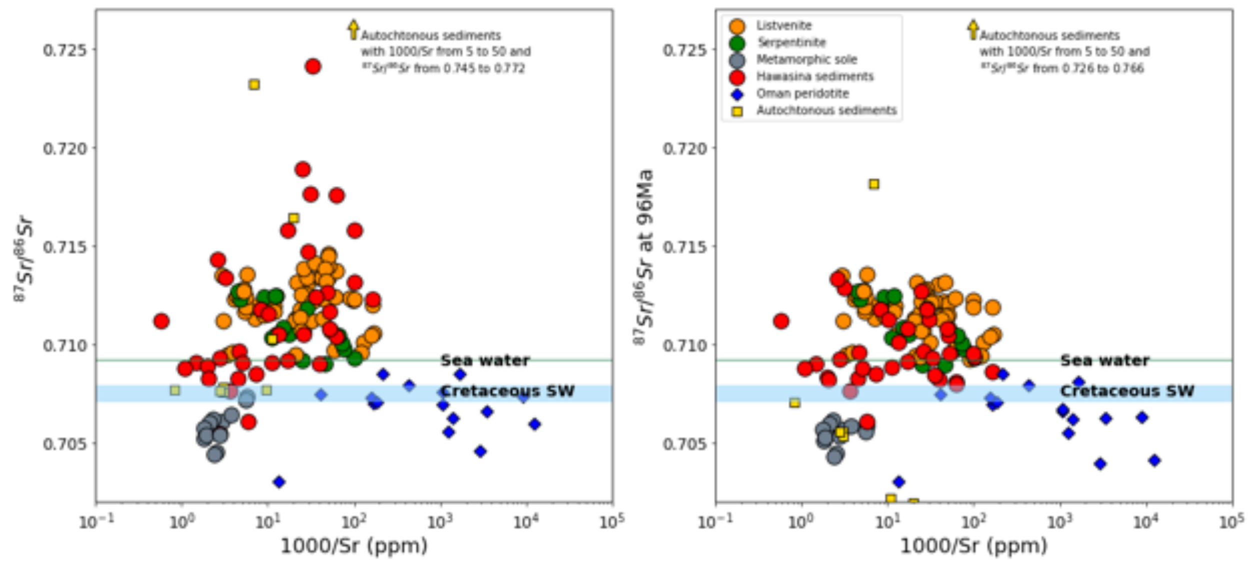


Figure 2. Measured (left) and age corrected at 96Ma (right) Sr isotope ratios and Sr concentrations for core samples from Oman DP Hole BT1B (large circles) compared to Sr isotope ratios in other lithologies measured in Oman. Hawasina sediments from this study and Falk and Kelemen (2015), leached peridotites from Gerbert-Gaillard (2002) and autochthonous sediment samples from Weyhenmeyer (2000). Rb concentrations were not reported for the autochthonous clastic metasediments, so an estimated upper bound Rb concentration of 200 ppm was used.

***3.2** Carbon concentrations and $\delta^{13}C$*

***3.2.1** Total Carbon*

The carbon contents of samples from Hole BT1B are highly dependent on lithology (Figure 3). All samples of ultramafic origin contain some carbon, mainly as Mg-rich carbonates, with serpentinites containing 0.2 to 5 wt% carbon, and listvenites containing 6 to 12 wt%. Samples from the metamorphic sole below 200 m depth contain 0.02 to 0.27 wt% carbon. In contrast, the Hawasina sediments have highly variable carbon contents. Some are almost pure metamorphosed limestones and dolomites with carbon contents of up to 11 wt%, while some have less than 0.05 wt% carbon.

$\delta^{13}C$ in the upper 200m of Hole BT1B varies significantly between serpentinites and listvenites (Figure 1). Serpentinites contain significantly lighter carbon than listvenites, as observed in the depth profile (Figure 1). The lower serpentinite band contains two samples (74-2 0.0-5.0 cm and 74-3 42.0-47.0 cm) that contain significantly lighter carbon than any serpentinite in the upper band. In general, carbon concentrations correlate positively with $\delta^{13}C$ values in the upper 200 m (Figure 3). Total carbon $\delta^{13}C$ values in the Hawasina nappes range from -5.52‰ to

3.69‰, which almost encompasses the entire range of variation observed in Hole BT1B and appears to decrease with lower carbon contents.

3.2.2 *Organic carbon*

Graphitic carbon was identified in the core both at the drill site and during core inspection aboard the D/V Chikyu (Kelemen et al, 2020, Kelemen et al. 2021). This organic component has a characteristic low $\delta^{13}C$ signature in listvenites and serpentinites from Hole BT1B, which extends to a minimum of -27.04‰, representing 0.05wt% of total carbon in the sample from 74-1 56.0-64.0cm (Figure 3). In some cases, the intermediate values likely represent mixtures of organic and inorganic carbon, as some of the magnesite in the listvenites is very resistant to 3N HCl attack and remain undissolved even after 5 days of leaching. The observed light isotopic compositions are similar to those observed in other ultramafic localities such as Cerro de Almirez and Liguria (Alt et al. 2013). These data confirm the presence of organic carbon in Hole BT1B, which was observed during drilling operations, core description aboard D/V Chikyu and via Raman spectroscopy (Kelemen et al, 2020, Kelemen et al. 2021).

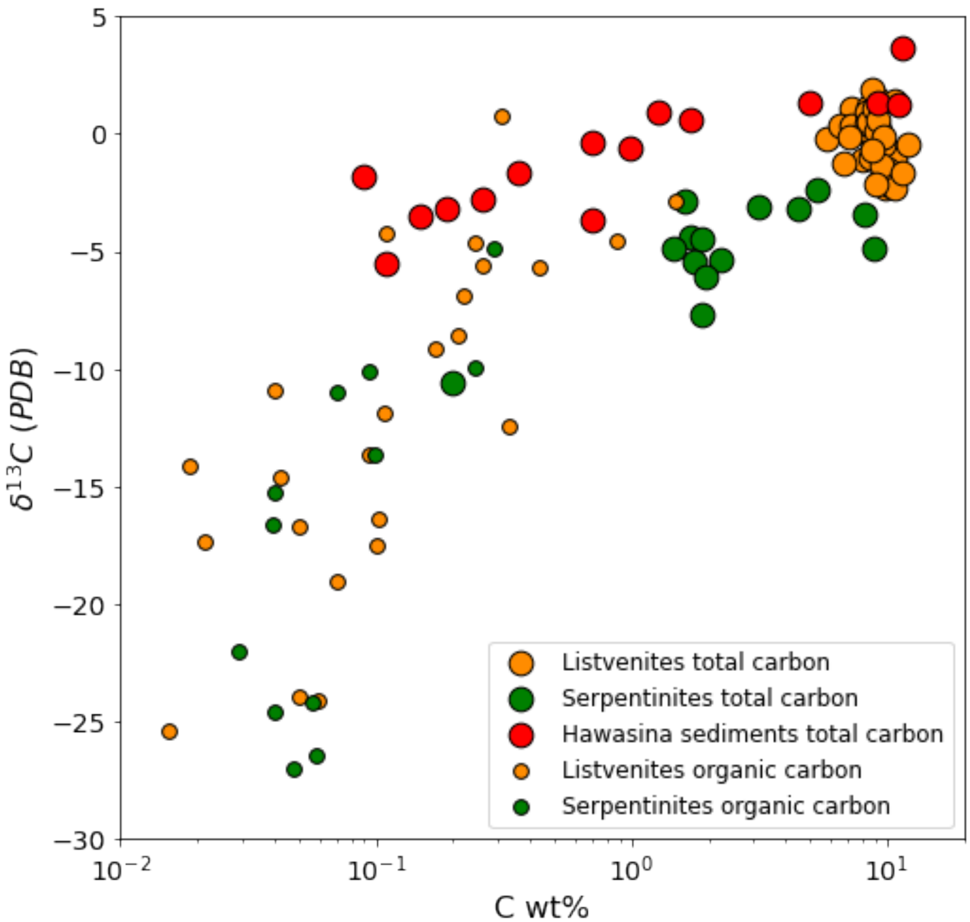


Figure 3. Total carbon and Total Organic Carbon (TOC) vs $\delta^{13}C$ for listvenites, serpentinites and Hawasina sediments.

4 Discussion

4.1 Temperature and pressure of listvenite formation

Falk and Kelemen (2015) estimated the temperature range of listvenite formation based on conventional and clumped stable isotope thermometry (90±15°C), phase equilibria (80-130°C), and rock textures. New clumped isotope measurements on BT1B drill core samples by Beinlich et al. (2020) widened the temperature range of listvenite formation and/or cooling from ~ 50±5 °C to 250±50 °C. This range of values suggests that the infiltrating reactive fluids had variable temperatures, and/or clumped isotope values were reset during cooling, as proposed for fine-grained samples of peridotite-hosted carbonate veins (Garcia del Real et al., 2016). The pressure of listvenite formation is very poorly constrained due to the lack of pressure-sensitive assemblages and the small size of fluid inclusions. A minimum pressure of 0.3 GPa is provided by the P-T conditions recorded by the carbonate platform during ophiolite obduction (Grobe et al., 2019). For the upper limit, the listvenites must have formed at a pressure below the maximum pressure reported for the metamorphic sole (~ 1.4 GPa) (Cowan et al., 2014; Searle and Cox, 2002).

4.2 Timing of listvenite formation

Falk and Kelemen (2015) used Rb/Sr and $^{87}Sr/^{86}Sr$ data on mineral separates to produce an imprecise isochron age of 97±29Ma for a listvenite sample. This age is broadly consistent with the ~96 Ma age of formation of igneous crust in the ophiolite, along with the same age of metamorphism for the underlying metamorphic sole just beneath the basal thrust of the ophiolite (Hacker, 1994; Hacker et al., 1996; Rioux et al., 2013**,** 2016**)**. Moreover, listvenites are found in and near the basal thrust, from the UAE near the northwestern end of the ophiolite outcrop to the area around Hole BT1B, near the southeastern end of the ophiolite outcrop in Oman (Nasir et al., 2007; Stanger, 1985). The extensive outcrop NE of Hole BT1B, known informally as MoD Mountain, exposes the Banded Horizon, a peridotite unit found at the base of the ophiolite mantle section composed of alternating 1- to 10-meter scale bands of dunite, harzburgite, and minor lherzolite. This unit has distinct geochemical characteristics, with higher Al and middle rare-earth-elements, compared to the residual mantle harzburgites that comprise most of the mantle section of the ophiolite (Boudier et al., 1988; Khedr et al., 2014; Prigent et al., 2018; Yoshikawa et al., 2015).

Tabular listvenites parallel to the dunite-harzburgite banding replace the Banded Unit, at and above the basal thrust. In this region, there is a consistent "stratigraphy" with peridotite (± listvenite) overlying the metamorphic sole, which in turn overlies the allochthonous Hawasina nappe. This stratigraphy is nearly flat-lying, forming a broad anticline with a NW trending hinge near the summit ridge of MoD Mountain, and a broad syncline that is coincident with the valley north of MoD Mountain. Throughout this region, the contacts of listvenite bands within and at the base of the Banded Unit are broadly parallel to banding in the peridotite, and to the contacts between listvenite, peridotite, metamorphic sole, and the Hawasina nappe. These data are consistent with our hypothesis that most of the listvenites formed by alteration of mantle peridotite during the subduction of the underlying sediments via intra-oceanic thrusting and/or later emplacement of the ophiolite onto the Arabian continental margin.

However, some of the listvenites formed or were modified during later events. The basal thrust of the ophiolite was regionally reactivated – mainly with normal sense displacements – during uplift and extension of the Jebel Akdar and Saih Hatat anticlinoria (Cawood et al., 1990; Coffield, 1990; Hanna, 1990; Mattern & Scharf, 2018). Some or all of the cataclasites in BT1B core and surrounding outcrops postdate listvenite formation and may record brittle deformation associated with this reactivation (M.D. Menzel et al., 2020). In turn, the listvenite cataclasites are fine-grained, indurated rocks – hard to drill or sample – that are cut by late, calcite and dolomite rich veins. Thus, it is clear that local fluid-rock interaction of the listvenites continued after brittle deformation.

On the basis of steep, fault-bounded contacts of listvenite with young, post-emplacement conglomerates, several workers have inferred that the listvenites formed during later uplift and extension (Nasir et al., 2007; Stanger, 1985; Wilde et al., 2002). Recently, Scharf et al. (2020) reported 60 ± 16 Ma and 58 ± 6 Ma U/Pb ages for two carbonate veins that cut listvenite, and structural observations indicating a top-down sense of shear along some faulted listvenite-peridotite and listvenite-sole contacts. Following prior interpretations, they interpret these ages as formation ages of the listvenites after ophiolite emplacement during uplift of the nearby Jebel Akdar and Saih Hatat anticlinoria. We find that their interpretation is inconsistent with the field observations reported above.

We have age-corrected our $^{87}Sr/^{86}Sr$ to the 96 Ma age reported by Falk and Kelemen (2015). This correction gives the lowest possible $^{87}Sr/^{86}Sr$ for all the samples based on reported ages. For the corrections, we used Sr and Rb concentrations reported by Godard et al. (submitted) for Hole BT1B and our analyses of Hawasina sediments. While Rb/Sr is low in most BT1B samples and thus age corrections are small, this correction removes some of the apparent trends observed in measured $^{87}Sr/^{86}Sr$ versus depth. The age corrections particularly affect listvenites with relatively abundant chromian mica (fuchsite-muscovite solid solutions, Falk & Kelemen 2015, supplement) in the 115-163 m depth interval, as these micas host abundant Rb (Godard et al. submitted). The age correction also affects the estimated $^{87}Sr/^{86}Sr$ values of the metamorphic sole of BT1B and some of the Hawasina sediments as their Sr and Rb concentrations are heterogeneous, ranging from 9 to 638 ppm for Sr and 0.4 to 97.7 ppm for Rb. Regardless, the age-corrected $^{87}Sr/^{86}Sr$ values of the listvenites are much higher than those of the mantle and Cretaceous seawater. The only plausible source of this radiogenic Sr is from the underlying Hawasina sediments.

4.3 Fluid source for carbonation of peridotites in Oman DP Hole BT1B

$^{87}Sr/^{86}Sr$ and $d^{13}C$ data on MoD Mountain listvenites and Hole BT1B samples suggest that replacement of peridotite by serpentinite and listvenite resulted from reaction with a single fluid along a reaction path (Kelemen et al. 2021). The initial fluid was far from equilibrium with peridotite, which converted olivine and serpentine in the protolith to carbonates + quartz and approached equilibrium with serpentinite at higher extents of reaction progress and lower integrated water/rock ratios (Beinlich et al 2020, Kelemen et al. 2021). Mg isotope data from a set of samples studied by Falk and Kelemen (2015) show significant differences between dolomite and magnesite listvenites. Dolomite listvenites (average $\delta^{26}Mg \sim -1.33$) are lighter in Mg isotopes than magnesite listvenites (average $\delta^{26}Mg \sim -0.33$) (de Obeso et al., 2021), which suggests magnesite dissolution and dolomite formation. This is consistent with the modelled evolution of listvenites during fluid-rock reaction, with dolomite replacing magnesite at increasing water/rock ratios (Kelemen et al. 2021).

As noted above, after the magnesite and dolomite listvenites formed they were cataclastically deformed, and then cut by late Ca-rich carbonate veins (Menzel et al. 2020). Thus, one might expect the veins to have formed from a later, geochemically distinctive fluid as suggested by variable clumped isotope ($\Delta 47$) derived temperatures (Beinlich et al., 2020). This can be addressed in future studies via careful sampling of the post-cataclastic veins.

Returning attention to the source of the fluid that formed the bulk of the listvenites, assuming that Sr and CO_2 were derived from the same fluid, Sr isotopes can be used to constrain the source of the carbonating fluids that formed the serpentinites and listvenites. Falk and Kelemen (2015) proposed three possible sources of fluids for carbonation: (1) compaction of pore waters from underlying Hawasina sediments, (2) low temperature dehydration of opal and clay minerals in calcite-bearing Hawasina sediments, and (3) higher-grade metamorphic devolatilization reactions involving subducted sediments similar to the Hawasina sediments coupled with fluid that migrated up the subduction zone.

Unlike younger, mantle-peridotite-hosted carbonates, the listvenites do not contain a significant fraction of seawater- or groundwater-derived Sr. The listvenites have $^{87}Sr/^{86}Sr$ ratios that are distinct from recent, low-temperature carbonate veins and travertine in the mantle section of the ophiolite (de Obeso & Kelemen, 2018; Peter B. Kelemen et al., 2011; Weyhenmeyer, 2000). Almost all of the listvenites and associated serpentinites from BT1B core and MoD Mountain outcrops have $^{87}Sr/^{86}Sr$ ratios at 96 Ma higher than Cretaceous seawater (Falk & Kelemen 2015, and this paper). In contrast, young, peridotite-hosted carbonate veins and travertines in the Samail ophiolite consistently have $^{87}Sr/^{86}Sr$ lower than 0.709 and appear to contain mixtures of Sr derived from seawater or groundwater and the mantle (de Obeso & Kelemen, 2018; Gerbert-Gaillard, 2002; Peter B. Kelemen et al., 2011; Weyhenmeyer, 2000).

In addition, the listvenites do not contain significant Sr from the metamorphic sole sampled in Hole BT1B. Core samples of the sole have $^{87}Sr/^{86}Sr$ ratios that are similar to Indian Ocean MORB and near-ridge Pacific seamounts (Hofmann, 2013), which are systematically lower than the Sr isotope ratios of the listvenites. Perhaps the metabasalts are remnants of a subducted seamount, similar to accreted seamounts along the Cascadia margin of North America (e.g., Duncan, 1982), which derived from the enriched mantle source of some Indian Ocean MORB. Alternatively, the $^{87}Sr/^{86}Sr$ ratios may have increased during alteration.

In contrast, age-corrected Sr isotope ratios for Hawasina sediments underlying the ophiolite and the metamorphic sole, north and northeast of Hole BT1B, have $^{87}Sr/^{86}Sr$ up to 0.7134 at 96 Ma (Figure 2). The samples with the most radiogenic $^{87}Sr/^{86}Sr$ are clastic sediments containing minor amounts of carbonates. Hawasina limestones, on the other hand, have lower $^{87}Sr/^{86}Sr$ values, which is consistent with calcite precipitated from seawater that incorporated a minor, radiogenic clastic component. Based on these observations, the most likely source of the fluids that formed the listenvites are derived from the Hawasina sediments.

Thermodynamic modeling of fluid-rock reactions (Kelemen et al. 2021) shows that the characteristic listvenite mineral assemblages – magnesite + quartz – are attained from fluids with ~ 20,000 ppm dissolved C for listvenite formation at 100-300 °C and 0.5 to 1 GPa, similar to the assemblages modeled by Klein and Garrido (2011) at lower pressures. Such high dissolved carbon contents are impossible to attain by congruent dissolution of pure calcite in aqueous fluids at these P-T conditions (Peter B. Kelemen & Manning, 2015), which rules out silicate-poor limestones such as those from the continental margin as a carbon source. On the other hand, metamorphic devolatilization of rocks composed of silicate-carbonate mixtures can produce C-rich fluids at temperatures above 400 °C and low to moderate pressures, depending on the rock composition. Thus, we infer that the fluids that formed the listvenites derived from devolatilization of subducting metasediments. During prograde subduction metamorphism, calc-silicate rocks, containing both clastic and carbonate components, undergo extensive devolatilization at 2-3 GPa and 500 to 700°C (Gorman et al., 2006; Stewart & Ague, 2020) and lose significant amounts of their CO_2 in this PT range due to reactions similar to the simplified reaction:

$$CaMg(CO_3)_2 \text{ (dolomite)} + CaMgSi_2O_6 \text{ (diopside)} + 2\ CaAl_2Si_2O_7(OH)_2 \cdot H_2O \text{ (lawsonite)}$$

$$= 2\ Ca_2MgAl_2Si_3O_{12} \text{ (garnet)} + 4\ H_2O + 2\ CO_2$$

In contrast, carbonate-rich compositions (limestone, dolomite, marble) are predicted to retain most of their CO_2 during subduction (e.g, (Kerrick & Connolly, 2001; Stewart & Ague, 2020)).

At temperatures greater than ~ 300°C, dissolved CO_2 in aqueous fluids have $\delta^{13}C$ values that are higher than those of co-existing calcite and dolomite (Chacko et al., 1991; Deines, 2004; Horita, 2014). Thus, for example, fluid in equilibrium with calcite with $\delta^{13}C$ between -4‰ to -6‰ (as in Hawasina clastic sediments) would contain dissolved CO_2 with $\delta^{13}C$ of -2.3‰ to -0.3‰ at 500°C. At lower temperatures, like those estimated for listvenite formation, calcite and dolomite have $\delta^{13}C$ higher than co-existing fluids. Thus, dolomite and presumably magnesite in equilibrium with fluids with $\delta^{13}C$ of -2.3‰ to -0.3‰ would have $\delta^{13}C$ in the range of -0.9‰ to 1.1‰, similar to the $\delta^{13}C$ observed in the listvenites from Hole BT1B and the surrounding outcrops.

Figure 4a illustrates that the listvenites and serpentinites from Hole BT1B lie along the reaction path proposed by Kelemen et al. (2021) at 200°C and 0.5GPa that forms listvenites with W/R~100. In our calculations, we assume that reacting fluids enriched in Sr (250 ppm) with $^{87}Sr/^{86}Sr$ values @96Ma that are similar to those of clastic Hawasina metasediments (0.7110 to 0.7135) reacted with the peridotite with mantle-like $^{87}Sr/^{86}Sr$ (0.7027±0.0011). The listvenites and serpentinites follow a mixing trend (Figure 4b) between mantle peridotite like compositions (Sr=1.5 ppm, $^{87}Sr/^{86}Sr$=0.7027±0.0011, C=680ppm and $\delta^{13}C$=6.0±2.0‰) and low temperature carbonates that crystallized from a fluid produced by high-pressure, high-temperature devolatilization with Sr isotope ratios in the range of the Hawasina clastic sediments (Sr=250ppm, $^{87}Sr/^{86}Sr$~0.7100 to 0.7135) and fractionated carbon isotopes as described above. These trends together suggest that the CO_2-bearing aqueous fluids that formed the listvenites from Hole BT1B and surrounding outcrops were derived by devolatilization of calc-silicate metasediments, with $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ similar to clastic sediments in the Hawasina Formation along a subduction zone geotherm. These fluids migrated up dip to lower pressures and temperatures to form the listvenites.

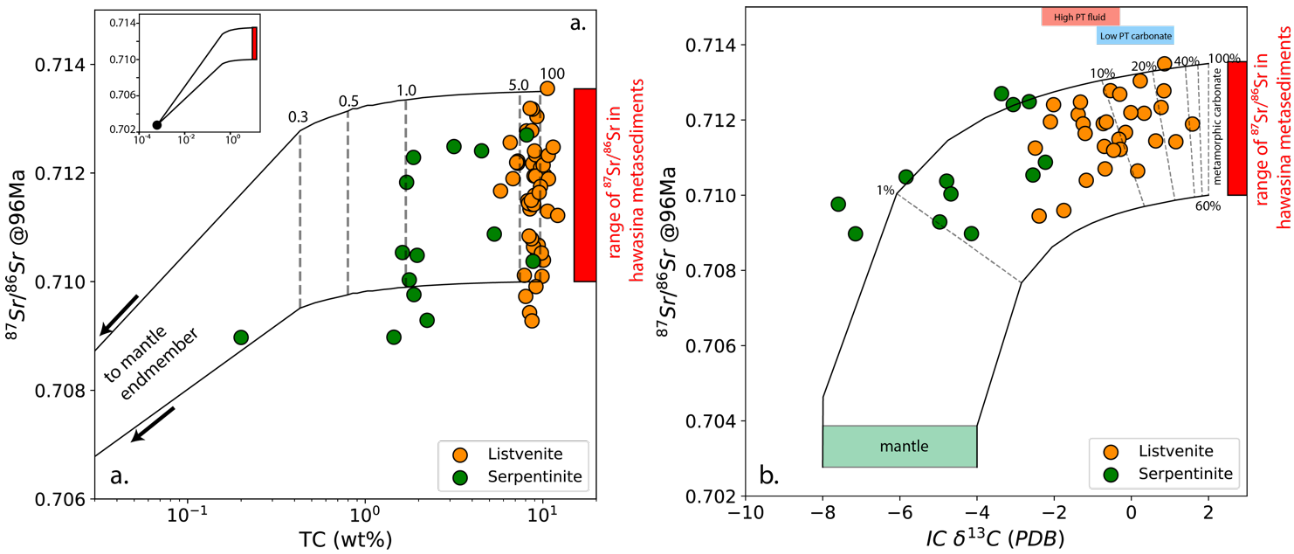


Figure 4. (a. left) Total carbon (wt%) vs $^{87}Sr/^{86}Sr$ @96Ma. Black lines are reaction paths of carbon rich fluid reacting with peridotite at 200°C and 0.5GPa at variable water/rock (tie lines) from Kelemen et al. (submitted). The reacting fluid is assumed to have $^{87}Sr/^{86}Sr$ values of 0.7100 to 0.7135 like those of clastic Hawasina metasediments. (b. right) Inorganic carbon $\delta^{13}C$ vs $^{87}Sr/^{86}Sr$ @96Ma. Black lines are mixing lines between mantle and carbonate minerals precipitated from a metamorphic fluid. The fluid has the same carbon concentration as the reaction path on the figure 4a and the $\delta^{13}C$ fractionation between the carbonate and the fluid are described in the body of the text with values for high and low PT shown top. We assume that the fluid has the Sr isotope ratios of Hawasina clastic sediments. $^{87}Sr/^{86}Sr$ values for the depleted mantle are for mid-ocean-ridge-basalt (MORB) from (Hofmann, 2013) . Mantle $\delta^{13}C$ is from (Deines, 2002).

5 Conclusions

Listvenites and spatially associated serpentinites from Hole BT1B and surrounding outcrops that replace residual mantle peridotites from the base of the Samail ophiolite have Sr isotope ratios that are more radiogenic than their peridotite protoliths, Cretaceous seawater, modern seawater, groundwater in the ophiolite, and the underlying metamorphic sole. We suggest that the radiogenic Sr isotope component was transported via carbon-rich aqueous fluid that reacted with the peridotite to form the listvenites and serpentinites. The $^{87}Sr/^{86}Sr$ values of this component resemble those of calcite-bearing clastic sediments in the Hawasina Formation underlying the ophiolite and the metamorphic sole. However, the fluid must have contained higher dissolved carbon contents than feasible for congruent dissolution of pure calcite at < 2 GPa and/or < 550°C. Thus, we hypothesize that this fluid was derived by devolatilization of carbonate- and silicate bearing meta-sediments akin to the Hawasina clastic sediments at 0.5 to 2.3 GPa and 400 to 700°C in the subduction zone (M. P. Searle et al., 1994). This fluid then migrated up dip to react with hanging wall peridotite at <1 GPa and <250°C, forming the listvenites and serpentinites. Carbon isotope fractionation during high temperature devolatilization followed by low temperature carbonate precipitation during the reaction with peridotite likely controlled the isotopic characteristics of the listvenites and the serpentinites with $\delta^{13}C$ from -10.6‰ to 1.92‰ and $^{87}Sr/^{86}Sr$ from 0.7090 to 0.7145.

6 Acknowledgments and Data

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Authors declare no conflict of interest.

All data will be uploaded to EarthChem or a similar repository prior to final publication.

7 References

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