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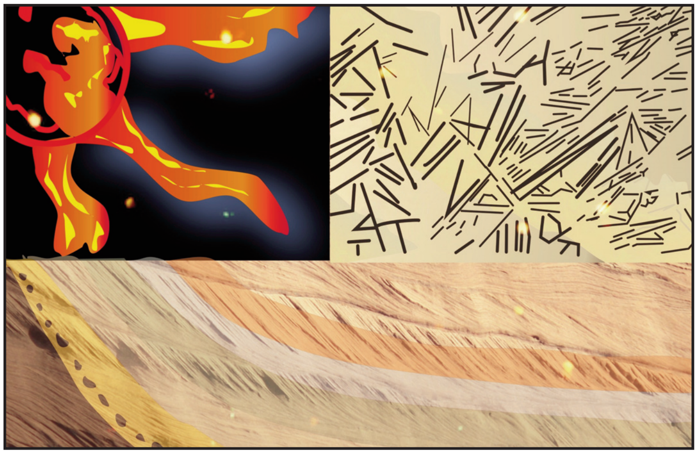
Article abstract

The crustal evolution of Venus appears to be principally driven by intraplate processes that may be related to mantle upwelling as there is no physiographic (i.e. mid-ocean ridge, volcanic arc) evidence of Earth-like plate tectonics. Rocks with basaltic composition were identified at the Venera 9, 10, 13, and 14, and Vega 1 and 2 landing sites whereas the rock encountered at the Venera 8 landing site may be silicic. The Venera 14 rock is chemically indistinguishable from terrestrial olivine tholeiite but bears a strong resemblance to basalt from terrestrial Archean greenstone belts. Forward petrological modeling (i.e. fractional crystallization and partial melting) and primary melt composition calculations using the rock compositions of Venus can yield results indistinguishable from many volcanic (ultramafic, intermediate, silicic) and plutonic (tonalite, trondhjemite, granodiorite, anorthosite) rocks that typify Archean greenstone belts. Evidence of chemically precipitated (carbonate, evaporite, chert, banded-iron formation) and clastic (sandstone, shale) sedimentary rocks is scarce to absent, but their existence is dependent upon an ancient Venusian hydrosphere. Nevertheless, it appears that the volcanic–volcaniclastic–plutonic portion of terrestrial greenstone belts can be constructed from the known surface compositions of Venusian rocks and suggests that it is possible that Venus and Early Earth had parallel evolutionary tracks in the growth of proto-continental crust.

SERIES



Igneous Rock Associations 28. Construction of a Venusian Greenstone Belt: A Petrological Perspective

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"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world" - Albert Einstein
"Every sentence I utter must be understood not as an affirmation, but as a question." - Niels Bohr

SUMMARY
The crustal evolution of Venus appears to be principally driven by intraplate processes that may be related to mantle upwelling as there is no physiographic (i.e. mid-ocean ridge, volcanic arc) evidence of Earth-like plate tectonics. Rocks with basaltic composition were identified at the Venera 9, 10, 13, and 14, and Vega 1 and 2 landing sites whereas the rock encountered at the Venera 8 landing site may be silicic. The Venera 14 rock is chemically indistinguishable from terrestrial olivine tholeiite but bears a strong resemblance to basalt from terrestrial Archean greenstone belts. Forward petrological modeling (i.e. fractional crystallization and partial melting) and primary melt composition calculations using the rock compositions of Venus can yield results indistinguishable from many volcanic (ultramafic, intermediate, silicic) and plutonic (tonalite, trondhjemite, granodiorite, anorthosite) rocks that typify Archean greenstone belts. Evidence of chemically precipitated (carbonate, evaporite, chert, banded-iron formation) and clastic (sandstone, shale) sedimentary rocks is scarce to absent, but their existence is dependent upon an ancient Venusian hydrosphere. Nevertheless, it appears that the volcanic–volcaniclastic–plutonic portion of terrestrial greenstone belts can be constructed from the known surface compositions of Venusian rocks and suggests that it is possible that Venus and Early Earth had parallel evolutionary tracks in the growth of proto-continental crust.

RÉSUMÉ
L'évolution de la croûte de Vénus semble être principalement déterminée par des processus intraplaques qui peuvent être liés à des remontées mantelliques, car il n'y a aucune preuve physiographique d'une tectonique des plaques semblable à la Terre (c.-à-d. dorsale médio-océanique, arc volcanique). Des roches de composition basaltique ont été identifiées sur les sites d'atterrissage de Venera 9, 10, 13 et 14 et Vega 1 et 2 tandis que la roche rencontrée sur le site d'atterrissage de Venera 8 peut être silicique. La roche du site de Venera 14 est indiscernable de la tholéiite à olivine terrestre de par ses propriétés chimiques, mais ressemble fortement au basalte des ceintures de roches vertes archéennes terrestres. La modélisation pétrologique prospective (c.-à-d. cristallisation fractionnaire et fusion partielle) et les calculs de la composition de fusion primaire à partir des compositions des roches de Vénus peuvent donner des résultats indiscernables de nombreuses roches volcaniques (ultramafiques, intermédiaires, siliciques) et plutoniques (tonalite, trondhjemite, granodiorite, anorthosite) qui caractérisent les ceintures de roches vertes archéennes. Les preuves de roches sédimentaires précipitées chimiquement (carbonate, évaporite, chert, formation de fer rubané) et clastiques (grès, schiste) sont rares ou absentes, mais leur existence dépend d'une ancienne hydrosphère vénusienne. Néanmoins, il semble que la partie volcanique-volcanoclastique-plutonique des ceintures de roches vertes puisse être construite à partir des compositions de surface connues des roches vénusiennes et suggère qu'il est possible que Vénus et la Terre primitive aient eu des trajectoires évolutives parallèles de croissance de la croûte proto-continentale.

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INTRODUCTION

Venus and Earth are often considered to be sister planets as they are similar in size, bulk composition, density, crater retention, and they have significant, albeit compositionally distinct, atmospheres (Table 1; Hansen 2018; Taylor et al. 2018). The modern exploration of Venus began in the 1960s and it was the first planet to be visited by a spacecraft (Mariner 2), have a probe soft-land on the surface (Venera 7), and to have surface pictures taken and sent back to Earth (Venera 9). Exploration of Venus continues to this day although the number of projects has waned since the successful Venera, Magellan, and Venus Express programs of the 1960s–1980s, 1990s, and 2000s (Basilevsky and Head 2003). Consequently, new discoveries have lagged behind that of other celestial bodies such as Mercury, Mars, Ceres, Titan, and Pluto. In spite of the lesser number of missions, new ideas and concepts on the evolution of Venus have been proposed in the past decade that could change the perception of Venus as an inhospitable hellscape. The new observations have led to suggestions that the crust of Venus may be differentiated (Hashimoto et al. 2008; Gilmore et al. 2015), that Venus may have sustained vast oceans until the middle Neoproterozoic (Way et al. 2016; Way and Del Genio 2020), that there was a climatic transition from relatively cool and wet that permitted deposition and erosion to hot and dry (Khawja et al. 2020; Byrne et al. 2021), that the surface age (~130 Ma) may be very young (Bottke et al. 2015), and that the conditions to support life may exist in the atmosphere (Seager et al. 2021).

The geology of Venus remains enigmatic as the physiographic features are known, but there is a dearth of detailed information on just about all other aspects (e.g. thermal regime, surface composition, sediment deposition) of crustal evolution (Basilevsky and Head 1988, 2003; Nimmo and McKenzie 1998; Ivanov and Head 2011). The surface of Venus is dominated (~ 80%) by relatively featureless volcanic plains that lie within ± 1 km of the mean planetary radius (mpr), whereas the remainder of the surface is composed of mesolands and highlands (Fig. 1; Basilevksy and Head 2003; Fegley Jr. 2014). The mesolands are moderately elevated, 1 km to 2 km above the mpr, and are known for their coronae (large oval volcanic domains) and chasmata (troughs) features. The highland regions represent ~ 8% of the surface and consist of tesserae terranes, large volcanic edifices, compression-related mountain belts, and may be compositionally different from the lowlands (Ansan and Vergely 1995; Basilevksy and Head 2003; Hashimoto et al. 2008; Gilmore et al. 2015). From the geomorphology of the crust, it is clear that Venus does not have Earth-like plate tectonics due to the absence of globe-encircling mid-ocean ridges and volcanic arc subduction zones (Nimmo and McKenzie 1998). However, the formation of the highlands is perplexing as it is not precisely known how or why thickened and compositionally differentiated crust can be voluminous in the absence of plate tectonics.

Different tectonic models have been proposed to explain the compressional, extensional, and deformational features and the higher elevations (> 3 km) of the highland terranes (tesserae). Models of highland formation are primarily focused on whether mantle upwelling or downwelling is the controlling factor in their development and maintenance (Bindschadler 1995; Jull and Arkani-Hamed 1995; Phillips and Hansen 1998; Hansen and Willis 1998; Hansen et al. 1999). The two largest highland terranes, Ishtar Terra and Aphrodite Terra, bear a striking resemblance to continental crust on Earth as they are elevated with respect to the volcanic plains and they appear to be older and at least partially deformed (Bindschadler and Head 1991; Ivanov 2001; Hashimoto et al. 2008; Romeo and Turcotte 2008; Gilmore et al. 2015). The apparent lack of plate tectonics and the existence of highland terranes on Venus has led to suggestions that Venus may be analogous to the pre-plate tectonics Archean Earth or possibly a post-plate tectonics setting (Hamilton 2007; Hansen 2007a, 2018; Harris and Bédard 2014). In fact, the vertical tectonic (mantle upwelling) model for the development of Venusian highland terranes is somewhat comparable to the 'unstable stagnant lid' model proposed for some granite–greenstone belts of Archean cratons (Harris and Bédard 2015; Bédard 2018). However, a major uncertainty with all geological analogues between Venus and Earth is whether the two planets have similar mantle compositions and structures, supracrustal rock types (komatiite, kimberlite, sedimentary rocks), or operated under similar tectonic regimes (plate tectonics).

Table 1. Physical properties of Venus and Earth.

Property	Venus	Earth
Radius	6052 km	6378 km
Mass	4.87 x 10^{24} kg	5.97 x 10^{24} kg
Bulk density	5.24 (g/cm^3)	5.51 (g/cm^3)
Albedo	59%	39%
Surface gravity acceleration	8.87 m/s	9.80 m/s
Average surface temperature	460°C	15°C
Atmosphere composition	N_2 (3.5%) O_2 (0-20 ppm) CO_2 (96.5%) H_2O (30 ± 15 ppm)	N_2 (78.1%) O_2 (20.9%) CO_2 (420 ppm) H_2O (4% to 40 ppm)

Values from Faure and Messing (2007).

The surface composition of Venus was measured at seven different locations between 20°S and 30°N across the volcanic plain and mesoland regions (Fig. 2; Kargel et al. 1993). The Venera 13, Venera 14, and Vega 2 landers analyzed, with the exception of Na_2O, the major elements, Cl, and SO_3 by X-ray fluorescence spectrometry (Table 2); whereas the Venera 8, Venera 9, Venera 10, Vega 1, and Vega 2 landers measured Th, U, and K by γ-ray spectrometry (Table 3; Vinogradov et al. 1973; Surkov 1977; Surkov et al. 1984, 1986, 1987). The rocks at the Venera 13 and Venera 14 sites are compositionally basaltic, but have distinct concentrations of CaO and K_2O. The compositional differences indicate the Venera 13 rock is alkaline (olivine leucitite or phonotephrite) whereas the Venera

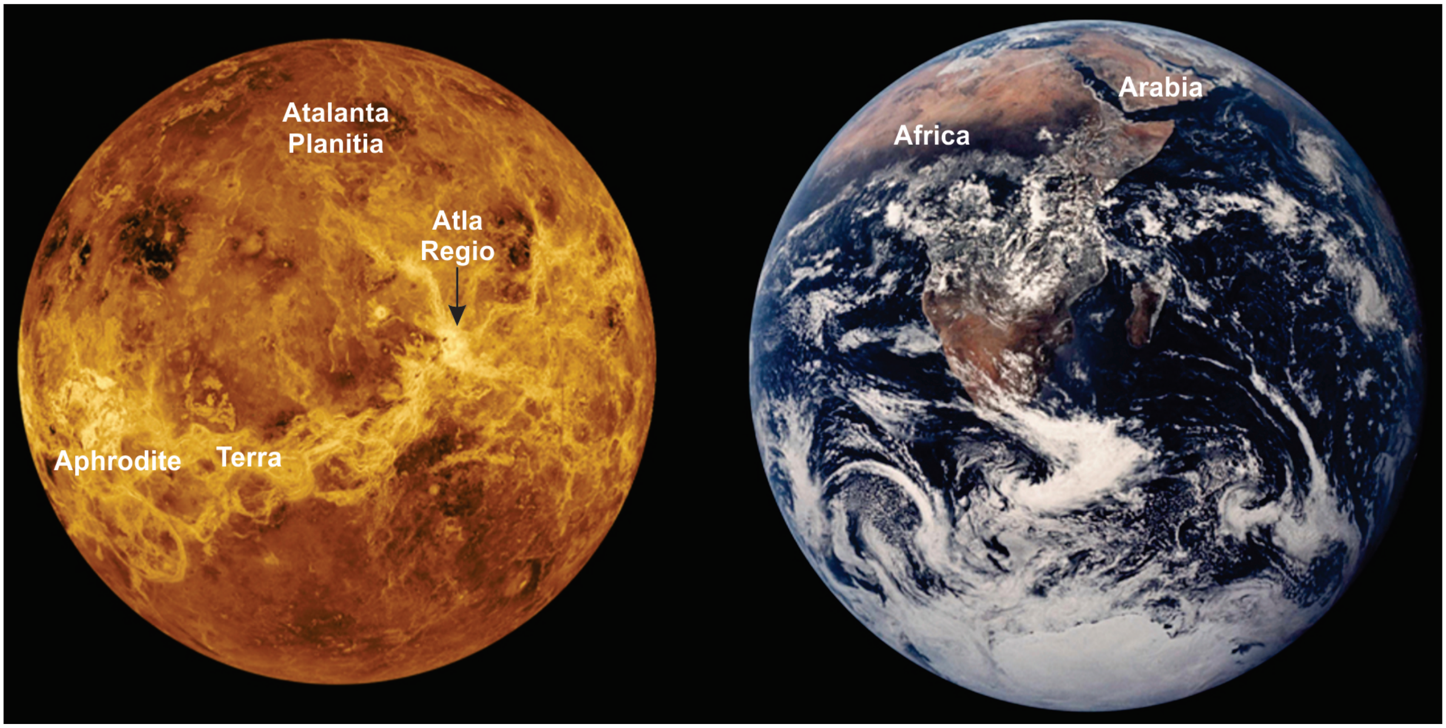

Figure 1. Size comparison of Venus and Earth. The Venus surface image is radar-based and false colour. Earth image from NASA/Apollo 17 crew.

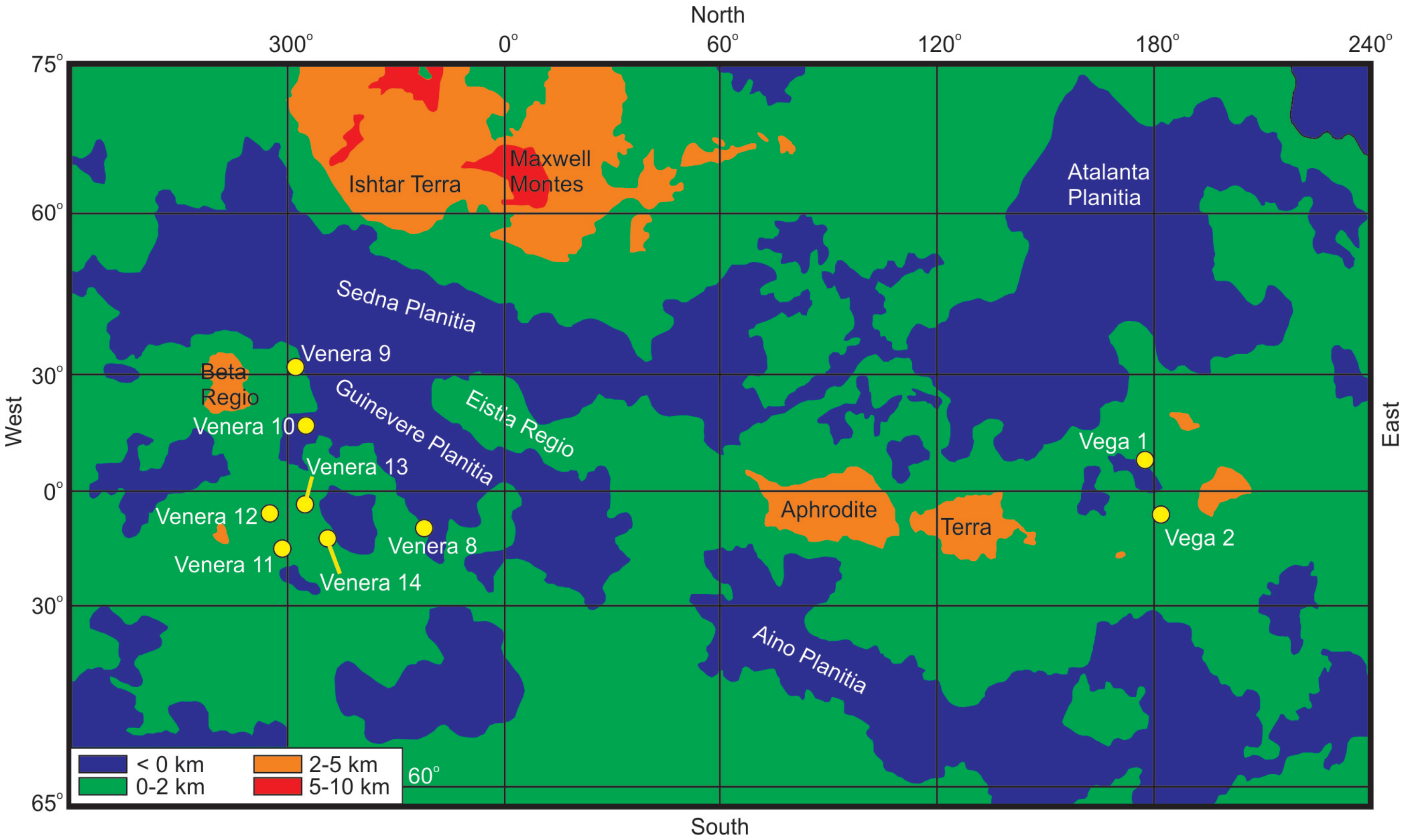

Figure 2. Mercator projection map of Venus showing the relative mean planetary radius crustal elevation and the locations of the Venera and Vega landers (modified from Faure and Messing 2007).

Table 2. Major element compositions of basalt from Venus, mid-ocean ridges, Archean greenstone belts, and the estimated composition of the Venera 8 rock.

Sample	Venera 13	Venera 14	Vega 2	Venera 8 (estimated)	N-MORB (mean)	E-MORB (mean)	Archean (DAT)	Archean (EAT)
SiO_2 (wt.%)	45.1 ± 3.0	48.7 ± 3.6	45.6 ± 3.2	58.3-65.6	50.42 ± 0.08	50.58 ± 0.33	50.90	50.91
TiO_2	1.6 ± 0.45	1.25 ± 0.41	0.20 ± 0.1	0.5-1.5	1.53 ± 0.04	1.53 ± 0.11	0.95	1.53
Al_2O_3	15.8 ± 3.0	17.9 ± 2.6	16.0 ± 1.8	13.4-16.2	15.13 ± 0.12	14.94 ± 0.38	15.72	15.63
FeO	9.3 ± 2.2	8.8 ± 1.8	7.7 ± 1.1	3.2-6.8	9.81 ± 0.15	9.64 ± 0.48	10.30	12.02
MnO	0.2 ± 0.1	0.16 ± 0.08	0.14 ± 0.12	0.1-0.2	0.17 ± 0.004	0.16 ± 0.013	0.22	0.19
MgO	11.4 ± 6.2	8.1 ± 3.3	11.5 ± 3.7	1.6-4.1	7.76 ± 0.09	7.37 ± 0.27	7.64	7.01
CaO	7.1 ± 1.0	10.3 ± 1.2	7.5 ± 0.7	2.8-6.4	11.35 ± 0.08	11.18 ± 0.27	11.76	9.04
Na_2O	2.0 ± 0.5*	2.4 ± 0.4*	2.0 ± 0.5*	2.5-4.4	2.83 ± 0.05	2.72 ± 0.18	2.18	2.78
K_2O	4.0 ± 0.6	0.2 ± 0.07	0.1 ± 0.08	3.4-4.9	0.14 ± 0.11	0.39 ± 0.075	0.22	0.71
P_2O_5				0.2-0.70	0.16 ± 0.004	0.24 ± 0.051	0.10	0.17
SO_3	1.6 ± 1.0	0.88 ± 0.77	4.7 ± 1.5					
Cl	< 0.3	< 0.4	< 0.3					
H_2O								
Th (ppm)			2.0 ± 1.0	6.4-6.7	0.25 ± 0.029	1.4 ± 0.23		
U (ppm)			0.68 ± 0.38	1.6-2.7	0.08 ± 0.008	0.39 ± 0.06		
Total	98.1	98.7	95.4					

All Venus basalt data reported at 1σ uncertainty. *The Na_2O content is calculated for the Venera 13, 14 and Vega 2 data (Surkov et al. 1984, 1986). The calculated Venera 8 composition is from Nikolayeva (1990). The mean (2σ) N-MORB (normal mid-ocean ridge basalt) and E-MORB (enriched mid-ocean ridge basalt) compositions are from Gale et al. (2013). Average Archean tholeiitic compositions from Condie (1981). DAT = depleted Archean tholeiite; EAT = enriched Archean tholeiite.

Table 3. Measured K_2O, Th and U contents from the surface rocks of Venus by g-ray spectrometry.

Sample	Vega 1	Vega 2	Venera 8	Venera 9	Venera 10
K_2O (wt.%)	0.45 ± 0.22	0.40 ± 0.20	4.0 ± 1.2	0.47 ± 0.08	0.30 ± 0.16
Th (ppm)	1.5 ± 1.2	2.0 ± 1.0	6.5 ± 2.2	3.65 ± 0.42	0.70 ± 0.34
U (ppm)	0.64 ± 0.47	0.68 ± 0.38	2.2 ± 0.7	0.60 ± 0.16	0.46 ± 0.26

The results reported by Surkov et al. (1987).

14 rock is sub-alkaline and similar to tholeiite from Archean greenstone belts and terrestrial within-plate settings (Fig. 3; Condie 1981; Filiberto 2014). The material measured at the Vega 2 landing site is unusual and may be representative of a soil–rock mixture as the reported SO_3 (4.7 ± 1.5 wt.%) content is very high. The remaining rocks are considered to be tholeiitic basalt or gabbro based on their Th–U–K contents (Fig. 4; Vinogradov et al. 1973; Surkov et al. 1986; Kargel et al. 1993; Treiman 2007).

There is significant uncertainty regarding the nature of the rock measured at the Venera 8 landing site as the Th (6.5 ± 2.2 ppm) and U (2.2 ± 0.7 ppm) concentrations are anomalously high and within the range of intermediate to silicic (granodiorite or dacite) igneous rocks (Nikolayeva 1990; Basilevsky et al. 1992). Nikolayeva (1990) suggested that the Venera 8 rock could be evidence of differentiated (continental?) crust but the K_2O (K_2O = 4.0 ± 1.2 wt.%) content of Venera 8 is indistinguishable from the value reported at the Venera 13 (K_2O = 4.0 ± 0.6 wt.%) landing site (Kargel et al. 1993; Treiman 2007). Subsequently, Basilevsky et al. (1992), due to the data uncertainty, concluded that the Venera 8 rock could be either an alkali basaltic rock (leucitite, minette, lamprophyre) or an evolved intermediate rock (diorite, granodiorite, syenite). The predominance of basaltic rocks encountered on the surface of Venus suggests that the planet may have retained its primary crust or that it is dominated by flood basalt of large igneous provinces or possibly the supracrustal successions of terrestrial Archean granite–greenstone belts (Harris and Bédard 2014; Hamilton 2015; MacLellan et al. 2021).

This contribution is a review of petrological modeling (fractional crystallization modeling, equilibrium partial melting, primary melt composition) that used the surface compositions measured at the Venera 13, Venera 14, and Vega 2 landing sites (Surkov et al. 1984, 1986, 1987). The modeling results are contextualized from within the framework of terrestrial geology and the formation mechanism of Archean supracrustal rocks as deduced from greenstone belts that typify the oldest cratons of Earth. The purpose of this manuscript is to demonstrate that the volcanic and sedimentary lithologies of terrestrial greenstone belts can be generated from rock compositions that are known to exist on the surface of Venus. Although the uncertainty in the data and the limited geological

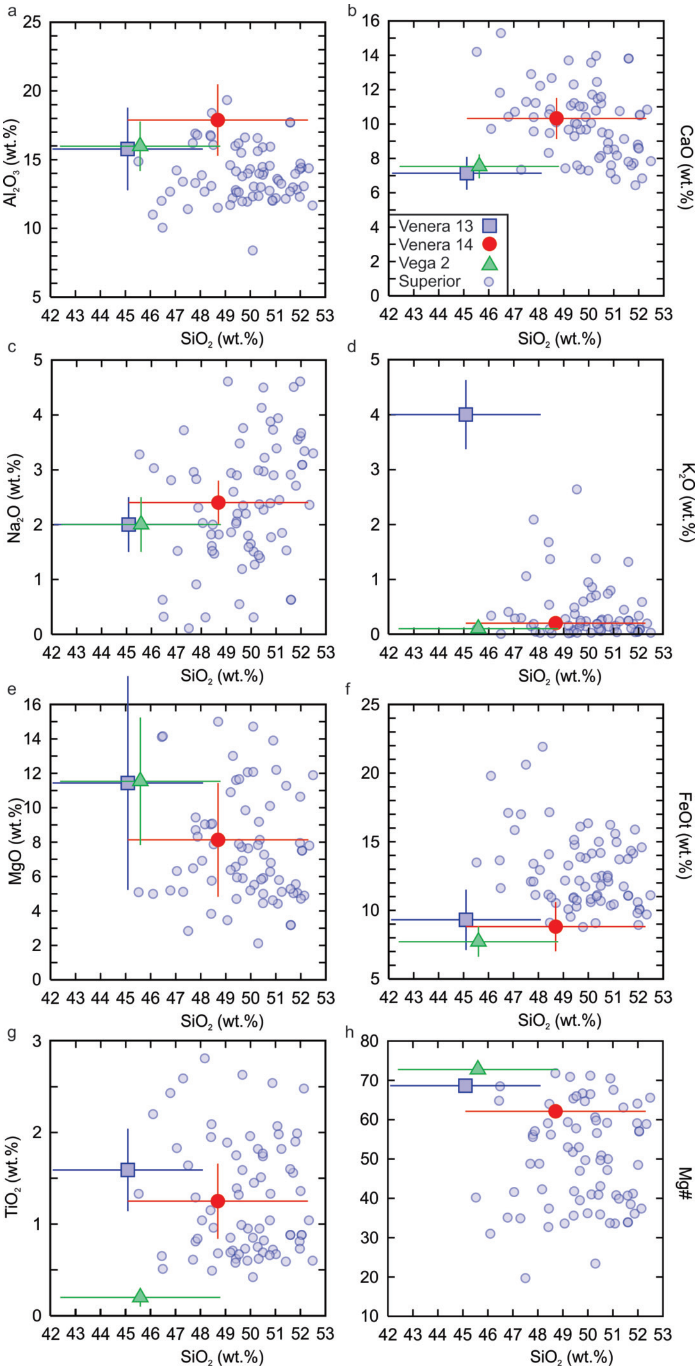

Figure 3. Major elemental comparison of Venusian basalt to tholeiitic basalt from Superior Province greenstone belts. All Superior Province data are from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/). The Superior Province basalt data were selected if the sum total was > 97 wt.% and < 101 wt.% without loss on ignition and MgO < 15 wt.%. Total iron was recalculated to FeOt (Fe_2O_3 wt.% = 0.8998 ´ FeO wt.%).

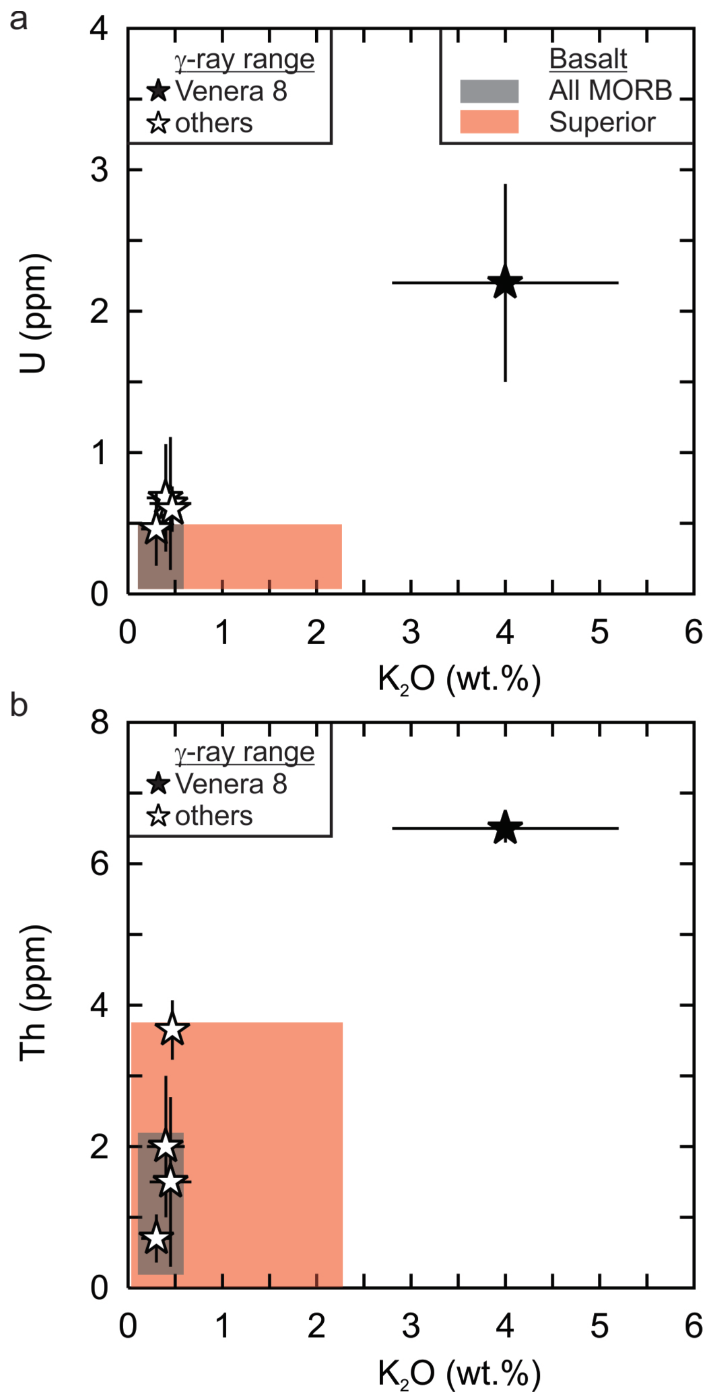

Figure 4. Trace elemental comparison of the Venusian basalts to all MORB and greenstone belt basalts from the Superior Province. All MORB values from Gale et al. (2013) and the Superior Province data is from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/).

knowledge of Venus prevents a firm conclusion, the findings indicate that the existence of greenstone belt-like crust on Venus cannot currently be dismissed. Therefore, I offer a hypothesis that is eminently testable for future missions to Venus.

SUMMARY OF MODELING PARAMETERS

Fractional crystallization and equilibrium partial melting modeling of the Venusian rocks were conducted using the petrological software MELTS (Shellnutt 2013) and Rhyolite-MELTS (Shellnutt 2018, 2019; Shellnutt and Manu Prasanth 2021). The magma conditions (initial temperature, relative oxidation state,

Table 4. Summary of MELTS and Rhyolite-MELTS modeling conditions.

Model	Pressure (GPa)	Relative oxidation state (fO_2)	Water content (wt.%)	Venera 13	Venera 14	Vega 2	Primitive Venera 14	Software version
2013								
FC	0.01, 0.1, 1.0	ΔFMQ 0	0, 0.2	✓	✓			M
PM	0.01, 0.1, 1.0	ΔFMQ 0	0, 0.2	✓	✓			M
2018								
FC	0.01, 0.1, 0.5	ΔFMQ 0, -1	0, 0.5			✓		R
PM	0.01, 0.1, 0.5	ΔFMQ 0, -1	0, 0.5			✓		R
2019								
FC	0.1, 0.5	ΔFMQ +0.7	0.4		✓			R
2021								
FC	0.1, 0.5, 1.0	ΔFMQ -1, 0, +1	0, 0.20, 0.5	✓	✓	✓	✓	R

FC = fractional crystallization; PM = equilibrium partial melting. M = MELTS (Smith and Asimow 2005); R = Rhyolite-MELTS (Gualda et al. 2012). FMQ = fayalite-magnetite-quartz buffer.
All models are isobaric conditions but the models of 2018, 2019, and 2021 include polybaric conditions. Primitive Venera 14 compositions were calculated by Shellnutt (2016).

water contents) used in the models encompass a wide range due to the uncertainties of the redox state, ambient temperature, and water content of the Venusian mantle (Table 4). However, conditions similar to terrestrial within-plate tectonic settings rather than subduction zone or mid-ocean ridge settings were used as a guide.

Pressure (1.0 GPa = ~ 35 km) is the least uncertain parameter and the model conditions range from surface to near surface (0.01 GPa), upper crust (0.1 GPa), middle crust (0.5 GPa), and lower crust (1.0 GPa). Most models presented here assume isobaric conditions, however polybaric models were also modeled (Shellnutt 2018, 2019; Shellnutt and Manu Prasanth 2021). The relative oxidation states of the models are within one log unit of the fayalite–magnetite–quartz buffer (ΔFMQ ± 1) as the FeO/MnO ratios of Venusian basalt (Venus basalt ≈ 52; bulk silicate Earth ≈ 60) are similar to bulk silicate Earth. Therefore, it is likely that the redox conditions of the Venusian mantle that produced the basalt is within two log units of the fayalite–magnetite–quartz (ΔFMQ ± 2) buffer, but could be slightly less oxidizing (Haggerty 1978; Schaefer and Fegley Jr. 2017).

The water content of the Venusian mantle is the most uncertain parameter. Evidence suggests Venus lost significant quantities of surface water and that the low but stable concentration of atmospheric water is maintained by atmosphere–mantle coupling (Donahue et al. 1997; Fegley Jr. 2014; Filiberto 2014; Gillmann and Tackley 2014; Airey et al. 2015; Way et al. 2016; Filiberto et al. 2020). Due to the uncertainty of the water concentration of the Venusian mantle, anhydrous (H_2O = 0 wt.%) and hydrous conditions were used in the hope that the conditions on Venus could be deduced indirectly from these models. For the basaltic models, 0.2, 0.4, and 0.5 wt.% water were used as these values are common for terrestrial basalt at within-plate settings (Hauri 2002). For the primary melt compositions, water was set to 0.2 wt.% as this is typical of primitive mafic and ultramafic volcanic rocks (Berry et al. 2008; Husen et al. 2013; Sobolev et al. 2016).

The primary melt composition and mantle potential temperature (T_P) estimates are calculated for Venera 14 using PRIMELT3 (Herzberg and Asimow 2015; Shellnutt 2016). The important parameters for the calculations are FeOt and MgO because they are the constituent components of olivine. The CaO content is also important because it indicates whether clinopyroxene and/or plagioclase were removed from the starting composition (i.e. Venera 14 composition). Consequently, the CaO content must be adjusted to prevent a clinopyroxene fractionation warning. The maximum and minimum permitted values of MgO, FeOt and CaO (± 1σ error) were used so that the T_P range can be constrained. The remaining elements (TiO_2, Al_2O_3, MnO, CaO, Na_2O and K_2O) are not major components of olivine and thus their variability will not significantly influence the estimates. The calculated primary melt compositions were then used for the Rhyolite-MELTS fractional crystallization modeling to investigate how the primary melts evolved after separation from the mantle (Table 5).

WHAT IS A GREENSTONE BELT?

A signature feature of all Archean cratons is the occurrence of granite–greenstone belts. Simply put, granite–greenstone belts are well preserved linear to curvilinear rock suites that are typically 10–25 km wide, 100–300 km long, 5 km−30 km thick and have a characteristic stratigraphy of volcanic rocks followed by volcaniclastic and sedimentary rocks that represent the final stages of maturation (Condie 1981; Bleeker 2002; Hawkesworth and Kemp 2006; Anhaeusser 2014; Thurston 2015). All greenstone belts are metamorphosed to some extent and intruded by granitic rocks (e.g. tonalite–trondhjemite–gra-

Table 5. Calculated primitive composition of the Venera 14 basalt and mantle potential temperature estimates.

Sample	Venera 14 (model 1)	Batch Melt	AFM	Venera 14 (model 2)	Batch Melt	AFM	AFM	Venera 14 (model 3)	Batch Melt	AFM
SiO_2 (wt.%)	48.7	49.11	49.13	48.7	46.41	46.47	46.66	48.7	48.06	48.13
TiO_2	1.25	1.26	1.26	1.25	1.07	1.08	1.12	1.25	1.19	1.20
Al_2O_3	17.9	17.97	18.01	17.9	15.26	15.44	15.99	17.9	17.05	17.22
Fe_2O_3		0.63	0.63		0.53	0.54	1.12		0.60	0.60
FeO		6.62	6.61		9.0	9.0	8.44		7.57	7.56
FeOt	7.1			9.7				8.1		
MnO	0.16	0.16	0.16	0.16	0.15	0.15	0.16	0.16	0.16	0.16
MgO	9.9	10.21	10.11	11.3	15.56	15.14	13.91	11.1	12.61	12.24
CaO	11.4	11.44	11.47	11.5	9.82	9.94	10.29	10.8	10.29	10.39
Na_2O	2.4	2.41	2.42	2.4	2.04	2.07	2.14	2.4	2.29	2.31
K_2O	0.2	0.20	0.20	0.20	0.17	0.17	0.18	0.20	0.19	0.19
SO_3										
Cl										
Total	99.01	100	100	103.11	100	100	100	100.61	100	100
Pressure (bars)		100	100		100	100	100		100	100
FeO (source)		8.02	8.02		8.02	8.02	8.02		8.02	8.02
MgO (source)		38.12	38.12		38.12	38.12	38.12		38.12	38.12
Fe_2O_3/TiO_2		0.5	0.5		0.5	0.5	1.0		0.5	0.5
Mole Fraction Fe^{2+}/Fe^*		0.92	0.92		0.94	0.94	0.88		0.93	0.93
% ol addition		0.6	0.3		13.0	11.8	8.2		4.3	3.3
F (%)		0.06	0.06		0.11	0.11	0.09		0.11	0.11
Temperature (°C)		1240	1240		1360	1350	1330		1300	1290
T_P (°C)		1310	1310		1450	1440	1410		1370	1360

AFM = accumulated fractional melt. F (%) = melt fraction. The model compositions above are entered into PRIMELT3 (Herzberg and Asimow 2015). The software automatically normalizes the data to 100% for the calculation. T_P (°C) = mantle potential temperature.

nodiorite) with many hosting significant deposits of base and precious metals (e.g. Au, Zn, Pb, Ni, Cu).

The terrestrial Archean volcanic sequences are typically composed of mafic subaqueous volcanic and volcaniclastic rocks with felsic intercalations and almost no sedimentary rocks. In comparison, the upper unit is primarily composed of sedimentary caprocks with few subaerial K-rich volcanic rocks (Fig. 5; Anhaeusser 2014; Thurston 2015). The lower portion of the volcanic unit consists of subaqueous ultramafic (komatiite) to mafic (tholeiite, boninite) volcanic rocks with minor felsic tuff layers. The upper portions of the lower unit consist of a bimodal sequence of tholeiitic flows and calc-alkaline mafic and silicic (andesitic to rhyolitic) volcanic rocks (Condie 1981; Anhaeusser 2014; Thurston 2015). In some cases the mafic–ultramafic sequences are separated by thin layers of calc-alkaline rocks at intervals ranging from 3 million years to 30 million years (Harris and Bédard 2014). Deposited on top of the volcanic series are sedimentary rocks, but the lithology of each greenstone belt is unique and can be composed of volcanogenic sandstone and mud-rocks, chemically precipitated carbonate rocks, sulphate chemically precipitated rocks (e.g. gypsum, barite), and banded iron formations, chert, jaspillitic sequences, conglomerate–quartz arenite–carbonate sequences, conglomerate–wacke–pelite, and tidal sand-wave deposits (Anhaeusser 2014). Furthermore, sedimentary depositional gaps also exist between volcanic episodes that range in duration from 2 to 27 million years (Thurston et al. 2008). The total duration of magmatism of a given greenstone belt is variable and can range from ~ 50 to ~ 300 million years (Percival and Card 1986; Corfu and Andrews 1987; Byerly et al. 1996; Anhaeusser 2014; Thurston 2015).

The intrusive complexes of greenstone belts include layered mafic intrusions (LMI), sill complexes, anorthosite plutons, and granitic suites (Bédard et al. 2009; Anhaeusser 2014; Ashwal and Bybee 2017). The layered intrusions are considered to be representative of magma chambers in which komatiitic and/or basaltic magma differentiated. Furthermore, anorthosite, and associated leucogabbro and gabbro, is a minor component of some greenstone belts (e.g. Abitibi, Fiskenæsset, Barberton). Anorthosite is principally formed by crystallization and accumulation of plagioclase from a mafic or ultramafic parental magma and occurs either as layers within LMI or as megacrystic lavas or sills (Ashwal and Bybee 2017). Among the granitic rocks that intrude greenstone belts are the tonalite–trondhjemite–granodiorite (TTG) suites that are considered to be generated by partial melting of hydrous mafic lower crust or possibly derived from subduction-related magmatic processes (Moyen 2011; Anhaeusser 2014).

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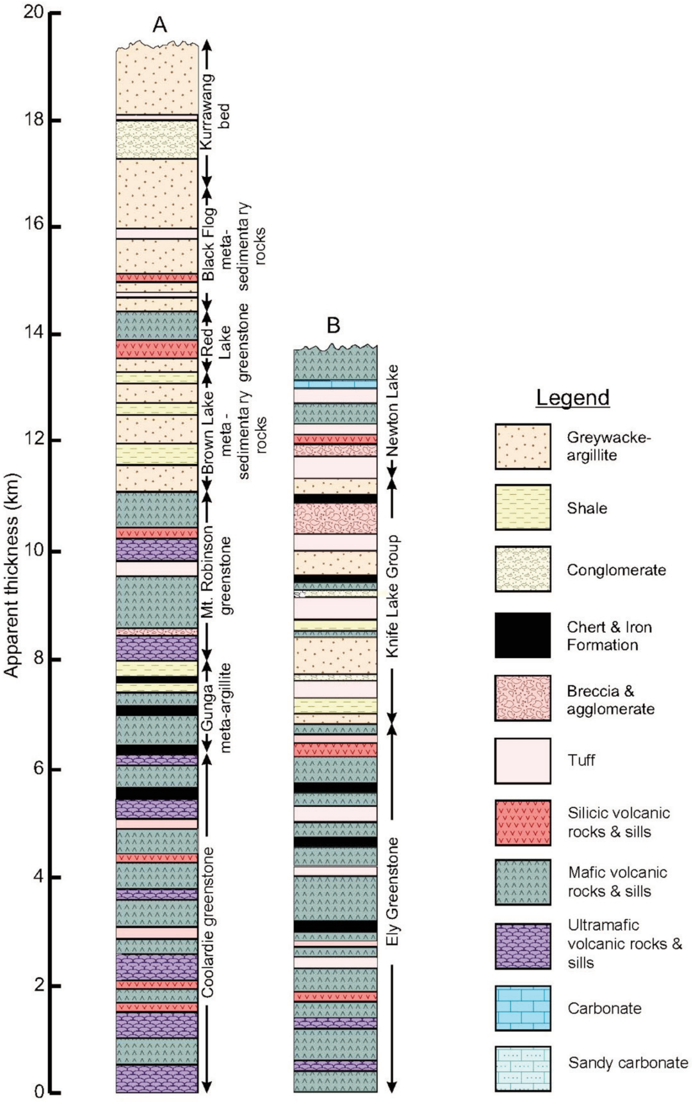

Figure 5. Greenstone belt stratigraphy of the Coolgardie–Kurrawang succession of Western Australia (A) and the Vermilion succession (B) of Minnesota (modified from Condie 1981).

The formation and origin (plate tectonic origin versus mantle-controlled) of greenstone belts has yet to be resolved as they are thought to be analogous to modern oceanic plateaus, volcanic arcs, ophiolites, or flood basalt suites that, at some level, may involve a mantle plume particularly with respect to the eruption of the lower mafic–ultramafic volcanic series (de Wit and Ashwal 1995; Bédard et al. 2003, 2013; Smithies et al. 2005a; Bédard 2006; Condie and Benn 2006; Anhaeusser 2014; Thurston 2015). The calc-alkaline nature of the silicic rocks in greenstone belts is, in some cases, considered to be evidence in favour of a volcanic arc-like origin for at least the silicic portion of the bimodal sequence (Scott et al. 2002; Wyman et al. 2002; Smithies et al. 2005b). It is likely that greenstone belts represent a glimpse into the development of primitive terrestrial crust or proto-continental crust (Smithies et al. 2005a; Thurston 2015; Bédard 2018).

TECTONOTHERMAL REGIME OF VENUS

The surface of Venus is dominated by low-lying volcanic plains that have a low crater density and an estimated crustal thickness of 10–15 km (Strom et al. 1994; Nimmo and McKenzie 1998; Byrnes and Crown 2002; James et al. 2013). Constraints on the interior processes, in particular the upper mantle, of Venus can be deduced from rock surface morphologies and compositions, large-scale physiographic features (rifts, folds, faults), and atmospheric composition (McKenzie et al. 1992a; Lee et al. 2009; Armann and Tackley 2012; Gillmann and Tackley 2014; O'Rourke and Korenaga 2015). The identification of large volcanic rises (e.g. Beta Regio), pancake domes (flat-top and steep-sided), coronae and novae (e.g. Mokos, Selu, Zemire), shield volcanoes (e.g. Maat Mons, Sapa Mons), and anastomosing lava channels indicate that Venusian lava flows have different viscosities and different compositions and/or represent different thermal regimes (Head et al. 1992; McKenzie et al. 1992b; Pavri et al. 1992; Kargel et al. 1993; Sakimoto and Zuber 1993; Lancaster et al. 1995; Nimmo and McKenzie 1998; Byrnes and Crown 2002; Buchan and Ernst 2021; MacLellan et al. 2021). The low crater density of Venus suggests volcanism was probably the main process of resurfacing and the maintenance of a young surface age, although the role of weathering and fluvial erosion in the denudation of surface features is possible, but not well established (Hauck et al. 1998; Smrekar et al. 2007; Kreslavsky et al. 2015; Way et al. 2016; Khawja et al. 2020). Hamilton (2005, 2015) offered an alternative explanation and suggested that Venus became geologically inert by 3.8 Ga due to less radiogenic heat, but this view is not widely adopted.

The absence of Earth-like subduction zones and mid-ocean ridges suggests that the interior cooling of Venus is probably facilitated primarily by advective heat transport either by mantle plumes or hotspots (Nimmo and McKenzie 1998; Phillips and Hansen 1998; Smrekar et al. 2007, 2010; Gillmannn and Tackely 2014; Gülcher et al. 2020; MacLellan et al. 2021). Conduction and rifting and mantle decompressional melting probably play important roles in mantle cooling as well. Accretion and differentiation models of Venus-like planets yielded bulk mantle compositions similar to Earth (FeO = 8.14 ± 0.90 wt.%), in particular the bulk FeO (4.52 to 8.25 wt.%) content (Herzberg and O'Hara 2002; Rubie et al. 2015). Consequently, mantle potential temperatures and primary melt compositions can be calculated from the Mg# of the Venusian basalt and offer estimates on the possible thermal regimes that operate on Venus as well as initial eruptive temperatures (Nimmo 2002; Lee et al. 2009; Filiberto 2014). A number of mantle potential temperature (T_P) estimates were calculated for Venus with temperatures of Venera 13 (T_P = 1459 ± 73°C) and Venera 14 (T_P = 1330°C, 1370 ± 70°C, 1459 ± 101°C) within the range of ambient conditions of modern Earth (i.e. T_P = 1350 ± 50°C); whereas estimates of Vega 2 (T_P = 1778 ± 167°C) are significantly higher and could be within the range of ambient Archean mantle, but the rock at Vega 2 may be representative of a soil–rock mixture (McKenzie et al. 1992a;

Lee et al. 2009; Weller and Duncan 2015; Shellnutt 2016, 2018). The initial melt composition of Venera 13 is difficult to calculate because the whole rock sum total is lower than that reported for the Venera 14 rock and it is alkaline, suggesting that was not in equilibrium with a low volatile lherzolitic mantle source (Table 5; Filiberto 2014).

The calculated thermal estimates and primary melt compositions are consistent with some of the volcanic morphologies (e.g. shield volcanoes, anastomosing lava channels) of the planitiae, although the pancake domes appear to indicate low viscosity lavas that may or may not be silicic (McKenzie et al. 1992b; Fink et al. 1993; Sakimoto and Zuber 1993). Nevertheless, as the range of model T_p similar to Earth have been calculated, the thermal regime and bulk composition of the Venusian mantle can be considered similar to the Earth, as it is consistent with known data. The possible thermal regime differences suggest that Venus may have had regions characterized by rapid eruption flux of mafic and ultramafic lavas (cf. Basilevsky and Head 2007; Hansen 2007b) and those of slower eruption rates expected for passive rifting (Basilevsky and Head 2002; Ivanov and Head 2015; Shellnutt 2016).

CONSTRUCTING A VENUSIAN GREENSTONE BELT

Lower Volcanic Sequence

When one builds a house it is wise to start with the foundation. The lower volcanic sequence of greenstone belts is commonly composed of spinifex-textured komatiite and primitive tholeiitic basalt with volcaniclastic rocks (Condie 1981; Anhaeusser 2014; Thurston 2015). The basalt measured at the Venera 14 landing site is compositionally similar to typical tholeiitic basalt of Archean greenstone belts and, more broadly, mafic volcanic rocks from continental flood basalt provinces or oceanic plateaus (Figs. 3 and 4). It is probably the only rock type from the Venus data set that can be identified with any degree of certainty and even then, the uncertainty of the measurement of Venera 14 is large.

The primary melt composition of Venera 14 was calculated using PRIMELT3 software and reported by Shellnutt (2016) and summarized in Table 5. Given the data uncertainty and the mantle redox conditions of the Venusian mantle, four primary melt compositions were calculated by accumulated fractional melting (AFM) whereas three were calculated using batch melting (Table 5). The AFM compositions, probably more representative of actual melt accumulation, show that the Venera 14 rock was either very close to a primitive basaltic melt or possibly a picritic melt as it has mantle potential temperature estimates ranging from 1310°C to 1440°C, and eruption temperatures of 1240°C to 1350°C. Although the picritic composition is ultramafic (MgO = 15.1 wt.%), it is not similar to a komatiite and the maximum mantle potential temperature estimate (1440°C) obtained is much lower than that expected for the terrestrial Archean (1500–1600°C) mantle (Herzberg et al. 2010). However, it does suggest that both mafic and ultramafic lavas can erupt on Venus. In this regard, it is expected that interlayering of mafic–ultramafic lavas and sills occurred and that would resemble the lower volcanic sequences of a greenstone belt. Whether komatiite-like lavas erupted on Venus or if subaqueous eruptions occurred is speculative at best, but considering the Venusian mantle was compositionally suitable to generate a rock similar terrestrial to olivine tholeiite, then it would be expected that they would exist at higher mantle potential temperatures.

Bimodal Volcanic Sequence

Overlying the lower mafic–ultramafic volcanic sequence of some greenstone belts is a bimodal volcanic sequence. The bimodal volcanic sequence consists of mafic tholeiitic (basalt, basaltic andesite) flows and intermediate (andesite, boninite) to silicic (dacite and rhyolite) calc-alkaline flows (Condie 1981; Anhaeusser 2014; Thurston 2015). The calc-alkaline nature of the intermediate to silicic rocks is considered to be evidence of an active margin (island arc or continental arc) origin for these rocks by some (Kohler and Anhaeusser 2002; Polat et al. 2002; Smithies et al. 2005b), but it is debated (Pearce 2008; Bédard et al. 2013; Barnes and Van Kranedonk 2014; Bédard 2018).

Intermediate and silicic igneous rocks have not conclusively been identified on the surface of Venus. The rock encountered at the Venera 8 landing site is currently the only hard evidence for the existence of an evolved igneous rock on Venus as it has high Th and U contents (Fig. 4). However, as discussed above, there are contrasting interpretations on the nature of the Venera 8 rock (Nikolayeva 1990; Basilevsky et al. 1992; Kargel et al. 1993). Ghail and Wilson (2015) identified large-scale, welded and possibly volatile-rich pyroclastic flow deposits, but there is little evidence at this moment to support or refute a silicic composition. Furthermore, pancake dome volcanic structures indicate that high viscosity lava flows erupted, but it does not confirm an intermediate or silicic composition (Fink et al. 1993).

Fractional crystallization modeling using the Venera 13, Venera 14, Vega 2, and the calculated Venera 14 primitive liquid compositions as the parental magmas yield intermediate to silicic compositions over a range of pressure, redox conditions, and water contents (Shellnutt 2013, 2018, 2019; Shellnutt and Manu Prasanth 2021). The modeled compositions include andesitic, trachytic, dacitic, rhyolitic, and phonolitic liquids. In other words, with the exception of foidite, many intermediate and silicic rocks described on the total alkalis versus silica diagram of Le Bas et al. (1986) can be generated by fractional crystallization of a spectrum of Venusian basalt. The Venera 13 alkaline basalt can generate the highly alkaline rocks (phonolite) after ~ 60% or more crystallization, whereas the subalkaline Venera 14 and Vega 2 compositions can yield the basaltic andesite–andesite–dacite–rhyolite series (Shellnutt 2013). The Vega 2 tholeiitic basalt can produce the trachytic liquid series under specific (e.g. hydrous, polybaric) conditions (cf. Shellnutt 2018).

Of particular interest is the Venera 8 rock because the Th–U–K contents indicate that it could be silicic. Using the Th–U–K contents of the Venera 8 rock, Nikolayeva (1990) calculated a likely bulk composition by comparing it to the distribution of the same elements in terrestrial rocks and concluded that it could be similar to granodiorite or dacite (Table 2).

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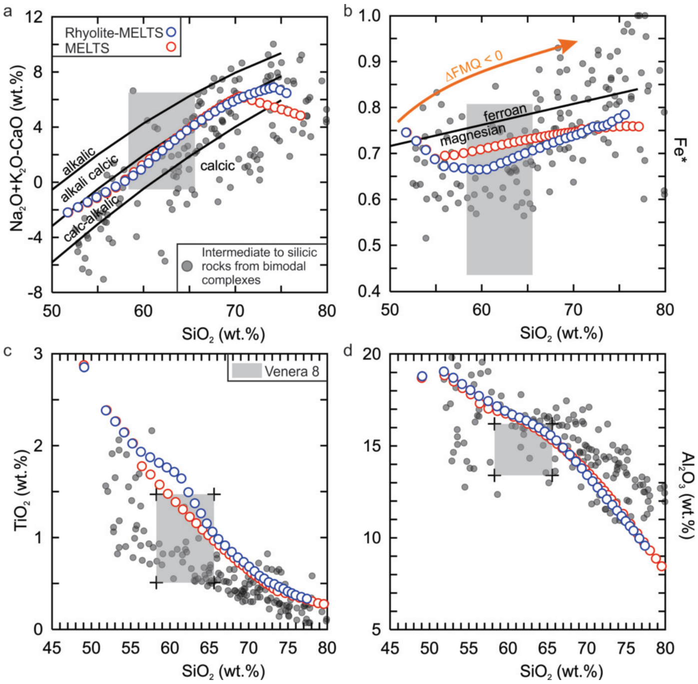

Figure 6. The results of the low pressure (0.1 GPa) MELTS and Rhyolite-MELTS models from Shellnutt (2019) compared to the silicic rocks of greenstone belts and Haida Gwaii using (a) the modified alkali–lime ($Na_2O+K_2O–CaO$) index (Frost et al. 2001), (b) Fe* [(FeOt/(FeOt+MgO))] value (Frost et al. 2001), (c) TiO_2 vs. SiO_2 and (d) Al_2O_3 vs. SiO_2. The calculated Venera 8 composition of Nikolayeva (1990) is shown in grey. Silicic rocks from greenstone belts (Uchi-Confederation, Wawa, Wutaishan, Gadwal, Central Bundelkhand) and the bimodal Masset Formation of Haida Gwaii. Data from Thurston and Fryer (1983), Sage et al. (1996), Polat et al. (2005), Manikyamba et al. (2007), Singh and Slabunov (2015) and Dostal et al. (2017).

Shellnutt (2019) demonstrated that fractional crystallization of a parental magma similar to Venera 14 subalkaline basalt could yield a residual silicic liquid within the range that Nikolayeva (1990) calculated. The modeling conditions that yielded the calculated Venera 8 composition were hydrous (H_2O = 0.4 wt.%), relatively oxidizing (ΔFMQ + 0.7), and polybaric crystallization. Moreover, not only did the Venera 14 subalkaline basalt fractional crystallization model yield compositions similar to the calculated Verena 8 composition, but the results also generated liquids that are similar to intermediate to silicic volcanic rocks from terrestrial Archean bimodal complexes (Fig. 6).

The formation of a bimodal volcanic sequence on Venus is plausible, more so with water and other volatile (Cl, F, CO_2) elements, and does not require unusual or special circumstances. The identification of pyroclastic deposits by Ghail and Wilson (2015) provides support for the possibility that both mafic and silicic volcaniclastic rocks would be present as well. The identification of rocks with basaltic composition is confirmed on Venus and it is expected that a mafic magma will yield a residual silicic liquid by fractional crystallization. Thus, bimodal volcanic complexes generated by fractional crystallization should exist on Venus. However, the formation of bimodal sequences of terrestrial greenstone belts is more complex than just fractional crystallization and involves assimilation–fractional crystallization (AFC) processes and the volcanism is likely cyclic (Leclerc et al. 2011). Assimilation–fractional crystallization (AFC) within Venusian volcanic and plutonic systems is expected, but there are no constraints on the composition of possible source rock (e.g. sedimentary rock, volcaniclastic rock) of the contaminant beyond the melt compositions that are generated by the fractional crystallization models.

Upper Sedimentary Sequence

The upper unit of greenstone belts is largely composed of sedimentary rocks with subordinate amounts of volcanic and volcaniclastic rocks (Condie 1981; Anhaeusser 2014; Thurston 2015). In many cases, the sedimentary sequences consist of lower chemically precipitated sedimentary rocks (carbonate rocks, banded-iron formation, and chert) and upper clastic sedimentary rocks (wacke, conglomerate, pelite). The changing nature of the sedimentary rock formations indicates terrestrial, shallow marine, marginal marine, and tidal zone depositional environments are possible (Anhaeusser 2014).

Key to the discussion on the existence of Venusian sedimentary rocks is the presence of a paleohydrosphere. At the moment, the atmosphere of Venus contains a stable amount (30 ± 15 ppm) of water vapour which is thought to be maintained by volcanic degassing (Grinspoon 1993; Zolotov et al. 1997; Fegley Jr. 2014; Filiberto et al. 2020). Furthermore, the high deuterium-to-hydrogen ratio (150 ± 30 times that of terrestrial water) indicates that Venus may have had a significant amount of surface water that was at least 4 m deep and possibly up to 530 m deep (Donahue et al. 1982, 1997). Atmospheric and planetary modeling indicates that Venus may have been able to sustain a hydrosphere until ~ 750 million years ago (Way et al. 2016; Way and Del Genio 2020).

Unconsolidated sediment was observed directly from the Venera 9, 10, 13, and 14 landers indicating that the Venusian surface experiences weathering and erosion (Florensky et al. 1983; Warner 1983). The sediments observed by the landers suggest that they were either deposited recently or that compaction has not occurred since their formation. At the moment, the evidence for lithified or chemically precipitated sedimentary rocks on Venus is limited, although Florensky et al. (1977) and Basilevsky et al. (1985) opined that a sedimentary origin of the rocks encountered at the Venera 9, 10, 13, and 14 landing sites is one of at least six possible interpretations. However, given their major and trace elemental compositions and assuming a sedimentary origin, then they would most likely be mafic volcaniclastic rocks. The rock compositions at the Venera 13, Venera 14, and Vega 2 landing sites reported relatively high SO_3 and Cl contents. Specifically, the Vega 2 (SO_3 = 4.7 ± 1.5 wt.%; Cl < 0.3 wt.%) site has high SO_3 content and it appears that the sample was likely a mixture of basaltic rock and regolith (Surkov et al. 1984, 1986). Although the data cannot distinguish between sulphide (S^{2-}) and sulphate (SO_4^{2-}), it is possible that the high sulphur content is due to the breakdown of evaporites, oxidation of sulphide minerals (gypsum, anhydrite, kieserite, langbeinite, polyhalite, kainite, barite, celestine, anglesite), or fumarolic activity. The whole-rock data certainly raise the possibility, although by no means definitive, that water existed on the surface and that chemically precipitated sedimentary rocks were deposited. If this was the case then it is conceivable that other chemically precipitated (chert, banded iron formation, carbonate) sedimentary rocks may have existed and that the rock units typical of the upper sedimentary sequences of greenstone belts could be present. Moreover, a Venusian hydrosphere would have accentuated deposition of clastic sedimentary rocks via weathering and erosion. There is evidence of channel erosion and possible folding of strata but the features may be of volcanic origin rather than sedimentary (Khawja et al. 2020; Byrne et al. 2021).

On Venus the formation of lithified epiclastic sedimentary rocks or chemically precipitated sedimentary rocks is uncertain and would be dependent on the existence of a paleohydrosphere. At the moment there is evidence for volcaniclastic deposits and erosional channels, and indications that sedimentary layering may exist in the highland terranes, but unequivocal identification of lithified or chemically precipitated sedimentary rocks is needed. Consequently, the development of an upper sedimentary sequence within a Venusian greenstone belt is the least constrained feature.

Anorthosite and Layered Mafic Intrusions

The oldest anorthosite bodies (≥ 2.4 Ga) on Earth are spatially and temporally associated with Archean greenstone belts. Archean anorthosite is also distinguished by its megacrystic, equidimensional plagioclase with anorthite contents (An% = $[Ca^{2+}/Ca^{2+}+Na^{+}+K^{+}]*100$) of An_{91} to An_{61} and have an average value of An_{80} (Ashwal and Bybee 2017). The megacrysts are commonly spherical, ~ 0.5 cm to > 30 cm in diameter, and are surrounded by a finer grained matrix of mafic silicate minerals (olivine, pyroxene) or a gabbroic groundmass (Ashwal 1993; Ashwal and Bybee 2017). Most Archean anorthosite intrusions are small (< 500 km^2) and likely developed within shallow crustal magma chambers (Phinney et al. 1988; Ashwal 1993; Polat et al. 2009; Ashwal and Bybee 2017). The initial melt composition that produced the anorthosite is thought to be primitive (komatiite, picrite, basalt) and may have experienced early high pressure crystal fractionation of olivine and/or orthopyroxene. Subsequent to high pressure fractionation, the less dense, hydrous, high Ca/Na and Al/Si tholeiitic melt migrates to a magma chamber within the shallow crust (0.1 GPa to 0.2 GPa) and crystallizes mafic silicate minerals and accumulates megacrystic plagioclase. It is possible that the plagioclase megacryst-rich magma is purged by new pulses of mafic melt into the magma chamber (Phinney et al. 1988). Of particular interest is the Venera 14 basalt (Mg# = 60 ± 15; Al_2O_3 = 17.9 ± 2.6 wt.%; CaO = 10.3 ± 1.2 wt.%) because it is similar to tholeiitic basalt of terrestrial Archean greenstone belts and the compositional range (i.e. Mg# = 35–60; Al_2O_3 = 14–18 wt.%; CaO = 9–15 wt.%) of the parental magmas that are thought to generate Archean megacrystic anorthosite (Ashwal and Bybee 2017).

Shellnutt and Manu Prasanth (2021) presented a comprehensive evaluation of the range of modeled plagioclase compositions from all known Venusian basalt that are expected to crystallize at low pressure (0.1 GPa), under variable redox states (ΔFMQ ± 1), and hydrous to anhydrous conditions. Plagioclase crystallizes relatively early (1230–1190°C) within all melt compositions (Venera 13, Venera 14, Vega 2) and is typically > 70 vol.% of the total mineral assemblage with the remaining ~ 30 vol.% being olivine (1370–1190°C). With such a high proportion of plagioclase crystallizing early and the density contrast with olivine (olivine ρ = 3.2–3.3 g/cm^3; plagioclase ρ = 2.6–2.7 g/cm^3), plagioclase could accumulate either by density stratification or convection redistribution to the point where it forms an anorthosite mush. The highest anorthite values from each low pressure model ranges from An_{85} to An_{77} (Table 6) and within the range of many Archean anorthosite examples (Fig. 7). The compositions of plagioclase after 50% of the total plagioclase crystallized range from An_{76} to An_{48}. The Venera 13 alkaline basalt models are the reason for the lowest anorthite contents (An_{68-48}) whereas the Venera 14- and Vega 2 subalkaline basalt models are more calcic (An_{76-70}). However, Archean anorthosite plutons are unlikely to be generated from alkaline magma (Ashwal and Bybee 2017).

As Venus has similar gravitational force (~ 91% of Earth) and similar basalt composition with similar temperature and phase relations, then it is likely that magma chambers would also exist. Layered mafic intrusions (LMI) are expected within the crust of Venus as the petrological processes of differentiation (e.g. fractionation) and crystal layering can occur. The estimated parental magma compositions of some terrestrial LMIs are broadly similar to the Venera 14 rock composition and would have similar liquidus phases (Table 7). Cumulus mafic minerals could generate layered mafic or ultramafic intrusions in the crust of Venus similar to those on Earth (e.g. Bushveld, Kiglapait, Muskox). From a crystallization point of view and assuming no crystal redistribution, an unlikely prospect, all models can yield cumulate rocks following the liquid line of descent of the modeling conditions (i.e. redox, pressure, water). Dunite (≥ 90 vol.% olivine) can be generated in the low (0.1 GPa) and medium (0.5 GPa) pressure models and some high (1.0 GPa) pressure models settings, as olivine is typically the liquidus mineral and is followed by plagioclase (troctolite) and then clinopyroxene (gabbro). The high pressure models can yield pyroxene-rich cumulate rocks (websterite, clinopyroxenite, orthopyroxenite). Some cumulate rock types could only be produced by specific parental compositions. For example, norite (opx + pl) was produced in the medium and low pressure Vega 2 models whereas harzburgite can be produced by the primitive Venera 14 compositions and wehrlite can be produced in Venera 13 models.

Venusian basaltic magma can produce LMIs in the crust and there is no reason why they could not develop cumulate monomineralic (anorthosite, dunite) layers or polyphase (gabbro, norite, troctolite, pyroxenite, websterite, wehrlite) layers (Pavri et al. 1992; Shellnutt 2013, 2018; Smith and Maier 2021). The principal uncertainties regarding the existence of LMI on Venus are their abundance, size, and thickness.

Tonalite–Trondhjemite–Granodiorite Suites

Tonalite–trondhjemite–granodiorite (TTG) suites are a common intrusive rock type within Archean cratons (Jahn et al.

Table 6. Summary of modeled plagioclase anorthite content (An%) compositions.

Model	Total An range			Initial An content			An content at 50% crystallization
P (GPa)	0.1	0.5	1.0	0.1	0.5	1.0	0.1
Anhydrous							
Vega 2a	79-23	78-13	75-16	79-77	78-77	75-71	74-72
Vega 2b	77-30	75-36	74-28	77-75	75-73	74-72	72-70
Venera 13	84-20	66-22	38-17	84-78	66-59	38-33	68-48
Venera 14	79-20	74-19	72-24	79-77	74-73	72-71	71-70
V14P1	80-13	78-15	73-17	80-79	78-76	73-71	76-72
V14P2	82-10	78-14	62-12	82-81	78-75	62-58	75-74
V14P3	80-11	79-14	73-17	80-79	79-73	73-70	73-72
Hydrous							
Vega 2a	82-30	82-11	78-5	82-81	82-81	78-76	76-75
Vega 2b	80-26	80-24	77-14	80-79	80-79	77-75	75-74
Venera 13	85-32	62-24	34-21	85-80	62-60	34-32	66-59
Venera 14	81-26	78-18	74-8	81-80	78-77	74-70	75-74
V14P1	82-16	78-13	74-8	82-81	78-76	74-71	75-72
V14P2	82-14	80-11	57-8	82-81	80-76	57-50	76-74
V14P3	82-16	79-12	73-8	82-80	79-75	73-66	75-74

Anorthite content (An%) = [(Ca^{2+}/(Ca^{2+}+Na^{+}+K^{+}))*100]. Anorthite contents are rounded to whole numbers across all redox conditions relative to the fayalite-magnetite-quartz buffer (ΔFMQ +1, 0, -1). Anorthite content at 50% crystallization is the compositional range of plagioclase when ~50% of all plagioclase in the system crystallized in the low pressure model. P = pressure in gigapascal.

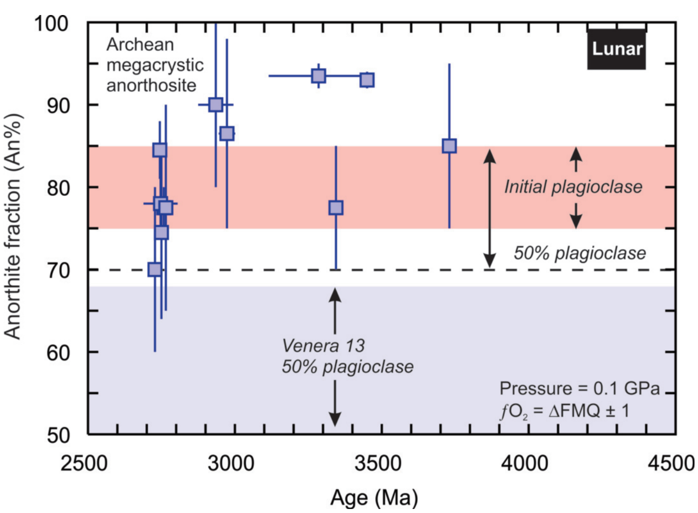

Figure 7. A comparison of modeled plagioclase compositions to those from Archean (≥ 2.5 Ga) megacrystic anorthosite (anorthosite data from Ashwal 1993). The range of initial plagioclase compositions from all models at shallow pressure (0.1 GPa) is shown in pink. The range of anorthite content at ~ 50% plagioclase crystallization for all models except Venera 13 is extended to the dashed line. The Venera 13 anorthite content at ~ 50% plagioclase crystallization is shown in light purple.

1981; Martin 1994; Martin and Moyen 2002; Moyen 2011; Moyen and Martin 2012). The TTG series is silicic (SiO_2 > 64 wt.%), sodic (Na_2O = 3.0 wt.% to 7.0 wt.%), and leucocratic (TiO_2+Fe_2O_3t+MnO+MgO ≈ 5.0 wt.%) with generally high alumina (Al_2O_3 > 15 wt.%) content at high SiO_2 (> 70 wt.%) content, depleted heavy rare earth element (HREE) signatures, and Mg numbers (~ 10 to ~ 70) that cover a wide range (Drummond and Defant 1990; Moyen 2011; Martin and Moyen 2012). It is thought that the TTG suites are derived primarily by partial melting of metamafic rocks extending from low to high pressure (< 1.0 GPa to > 2.5 GPa) conditions across a range of proposed geodynamic settings that include orogenic/subduction and anorogenic (Moyen 2011; Bédard et al. 2013; Johnson et al. 2017).

Although Venus does not appear to have Earth-like plate tectonics, there are compressional features (e.g. Ishtar Terra) and possibly structures related to subduction or underthrusting-like structures (e.g. Artemis corona) that suggest horizontal and vertical thickening both occurred (Suppe and Connors 1992; Davaille et al. 2017). Moreover, crustal thickness estimates suggest that some regions of the highland terranes may exceed 30 km and up to 65 km (Head 1990; James et al. 2013; Harris and Bédard 2015). Therefore, it is possible that partial melting of tectonically thickened Venusian mafic crust could yield magmas that fall within the range of the TTG series. In fact, the Venera 14 composition is somewhat similar to the 3.5 Ga Coucal Formation basalt of the lower Pilbara Supergroup of Western Australia. Johnson et al. (2017) demonstrated by phase equilibria modeling that the Coucal basalt can yield TTG magmas after 20–30% partial melting along a high geothermal gradient (700°C/GPa).

Shellnutt (2013) showed that hydrous (0.2 wt.%) equilibrium partial melting of the Venera 14 sub-alkaline basalt at 1 GPa under moderately oxidizing conditions (ΔFMQ 0) will yield liquid compositions at 1040°C to 950°C that are very

Table 7. Major elemental compositions of the Venera 14 basalt and proposed parental magma compositions of layered mafic intrusions.

Sample	Venera 14	Skaergaard	Kiglapait	Stillwater	Bushveld Critical Zone	Bushveld Upper Zone
SiO_2 (wt.%)	48.7 ± 3.6	48.1	47.97	49.41	48.50	49.32
TiO_2	1.25 ± 0.41	1.17	1.24	1.20	0.75	0.81
Al_2O_3	17.9 ± 2.6	17.2	18.95	15.79	16.49	15.67
FeO	8.8 ± 1.8	9.6	11.67	12.14	12.41	12.77
MnO	0.16 ± 0.08	0.16	0.14	0.20	0.19	0.19
MgO	8.1 ± 3.3	8.6	7.67	7.36	7.57	6.08
CaO	10.3 ± 1.2	11.4	8.60	10.88	11.15	10.83
Na_2O	2.4 ± 0.4*	2.34	3.21	2.19	2.17	2.94
K_2O	0.2 ± 0.07	0.25	0.40	0.16	0.14	0.25
P_2O_5		0.10	0.13	0.11	0.18	0.07
SO_3	0.88 ± 0.77					
Cl	< 0.4					

Uncertainty of Venera 14 data is at 1σ level. *The Na_2O content is calculated for the Venera 14 rock (Surkov et al. 1984). Proposed parental magma compositions of the Skaergaard intrusion (McBirney 1996), Kiglapait intrusion (Morse 2015), Stillwater Complex (McCallum 1996), and the Critical Zone and Upper Zone of the Bushveld Complex (Eales and Cawthorn 1996).

similar to TTG suites after 6–8% melting (Fig. 8). The estimated tectonothermal conditions of Venus are sufficient to melt mafic crust at the modeled primary liquid temperatures and the modeling pressure is within the range of crustal thickness estimates (> 30 km) of Ishtar Terra and Ovda Regio regions (James et al. 2013; Harris and Bédard 2015). Therefore, it is conceivable that TTG-like magmas could form within the highland regions of Venus provided that the base of the crust was broadly similar to olivine tholeiite and moderately hydrous. The models using the Venera 13 and Vega 2 compositions could not yield TTG-like compositions by equilibrium partial melting because they are either too alkaline or deficient in silica.

Summary

The modeling results indicate that the principal lithologies of terrestrial Archean granite–greenstone belts can be formed from the known rock compositions of Venus. There is significant uncertainty in the generation of the chemically precipitated sedimentary sequences, but unlithified sediments do exist on Venus and it is possible that lithified clastic sedimentary rocks also exist. Therefore, it is possible that Venus and Earth may have evolved along similar paths from the Hadean to the Neoarchean. The implication is that Venus may provide evidence for the development of proto-continental crust of Earth prior to the initiation of plate tectonics.

WAS EARLY VENUS ANALOGOUS TO ARCHEAN EARTH?

One of the most important first order geological features of Venus is the dichotomy between the low crater density of the crust and the apparent absence of modern Earth-like plate tectonics. The estimated crater retention surface age of Venus is fairly young (≤ 1 Ga) in comparison to Mars or the Moon (Turcotte 1993; Strom et al. 1994; Basilevsky and Head 2002; Herrick and Rumpf 2011; Bottke et al. 2015; Fasset 2016) although Hamilton (2007) suggested that the surface of Venus could be closer to ~ 3.8 Ga. The absence of a planet-wide geodynamic mechanism responsible for maintaining a low crater density and generating morphologically and tectonically distinct terranes is perplexing. Given the absence of plate tectonics, the most likely explanation for the young surface features of Venus is advective transport of mantle material via hotspots or mantle plumes that may periodically and/or catastrophically erupt (Phillips and Hansen 1998; Ernst and Desnoyers 2004; Hansen 2007b; Romeo and Turcotte 2010; Smrekar et al. 2010; Smrekar and Sotin 2012; O'Rourke et al. 2014; Ghail 2015; Ivanov and Head 2015; Kreslavsky et al. 2015; Gülcher et al. 2020; Uppalapati et al. 2020). It is from this perspective that Venus is frequently considered as an analogue for Archean Earth as it is thought that modern plate tectonics did not commence until ~ 2.5 billion years or later and that the tectonic regime was mostly driven by a vertical process, that is, mantle plume-initiated rifting and collision (Smithies et al. 2005a; Condie et al. 2016; Bédard 2018; Brown et al. 2020; Dewey et al. 2021).

Compared to the Phanerozoic (~ 540 Ma to present) or even the Proterozoic (~ 2.5 Ga to ~ 0.54 Ga), less is known about the tectonic regime and development of the Archean (~ 4.0 Ga to ~ 2.5 Ga) Earth due to the progressive degradation of the geological record (Brown et al. 2020; Hawkesworth et al. 2020). Moreover, there is debate on the timing of plate tectonics initiation (Condie and Kröner 2008; Stern 2008; Hamilton 2011, 2019; Dewey et al. 2021). However, most agree that the thermal regime under which Archean crust developed was 300°C to 500°C higher than ambient conditions of today (T_P = 1350 ± 50°C). There is virtually no rock record of the Hadean (~ 4.5 Ga to ~ 4.0 Ga) as most of the information is inferred from the Acasta Gneiss, detrital zircon, or isotopic

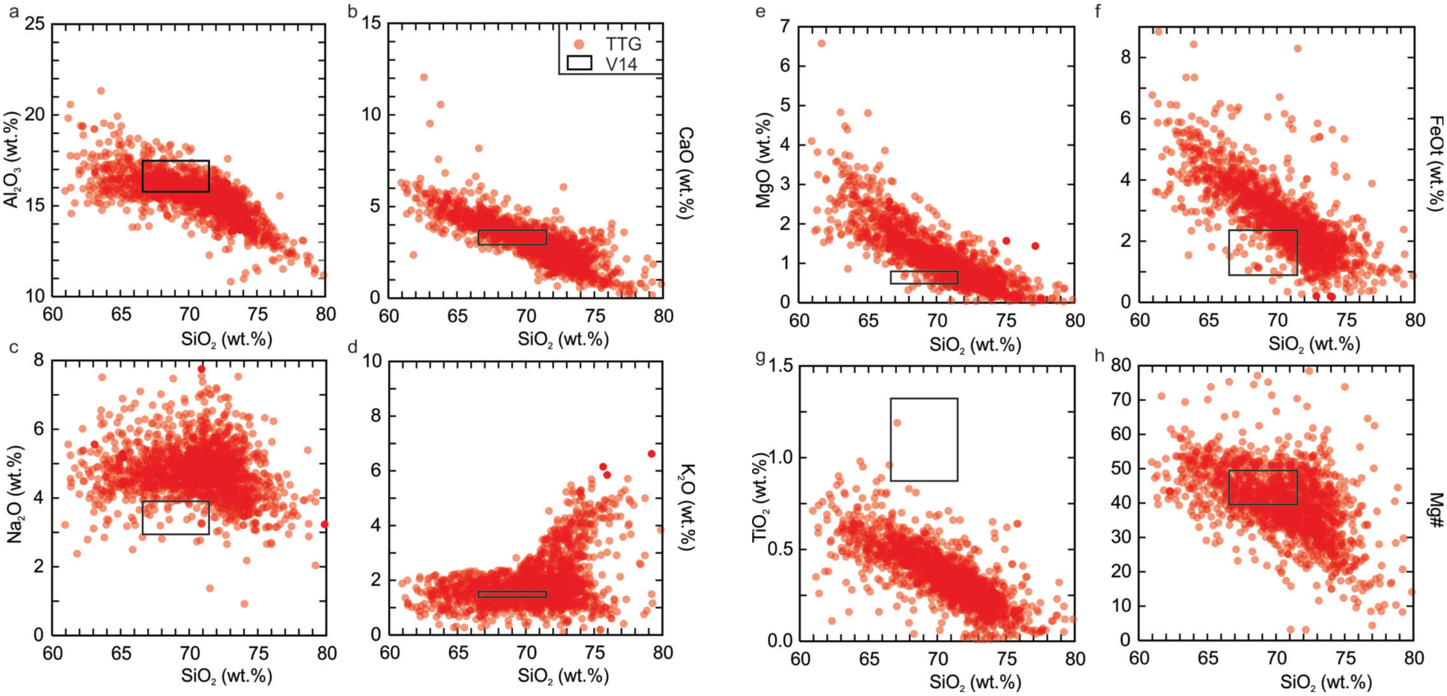

Figure 8. Major elemental comparison of the high pressure (GPa = 1.0) partial melts of the Venera 14 rock (in outlined box) to tonalite–trondhjemite–granodiorite (TTG) rocks. TTG data from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/) and all data are recalculated to 100% on an anhydrous basis.

model ages (Harrison 2009; O'Neil et al. 2012; Roth et al. 2014; O'Neil and Carlson 2017; Reimink et al. 2020). It is likely that granite–greenstone and granulite–gneiss belts of Archean cratons represent a glimpse into the formation of primitive terrestrial crust or proto-continental crust (Smithies et al. 2005a; Van Kranendonk 2010; Thurston 2015; Bédard 2018). Of the two belts, the granite–greenstone belts are probably more widely known as they are a major source of gold and record supracrustal rock sequences whereas the granulite–gneiss belts record middle to lower crust metamorphic conditions, but may have protoliths of rock sequences from the upper to middle crust (Condie 1981).

The surface of Venus is broadly divided into low-lying (~ 90%) volcanic plains (planitia) and that are dominated by volcanic features (e.g. shield volcanoes, pyroclastic flows, lava channels) and highland (> 2 km) regions of older and deformed tesserae terrain and mountain belts (Lancaster et al. 1995; Nimmo and McKenzie 1998; Herrick et al. 2005; Smrekar et al. 2010; Airey et al. 2015; Ghail and Wilson 2015; Gilmore and Head 2018; Gülcher et al. 2020). At first glance the topography of Venus resembles the continental and oceanic crust dichotomy of Earth where the tesserae represent 'continental' or sialic crust and the planitiae represent 'oceanic' or simatic crust (Fig. 2). Crustal thickness estimates indicate that the planitiae could be 10–20 km thick whereas the tesserae may be up to ~ 65 km thick, although there are a number of different estimates (Head 1990; Anderson and Smrekar 2006; James et al. 2013; Harris and Bédard 2015). Near-infrared mapping spectrometer data suggest the plains (low SiO_2, high MgO, high FeOt) and tesserae (high SiO_2, low MgO, low FeOt) are compositionally different (Hashimoto et al. 2008; Basilevsky et al. 2012). The crustal thickness estimates of Venus are within the range of granite–greenstone belts (10–20 km) and granulite–gneiss belts (~ 40 km) and the surface chemical mapping is consistent with the compositional differences between terrestrial continental and oceanic crust. The major elemental composition of basalt measured at the Venera 14 landing site is similar to olivine tholeiite of Archean greenstone belts and the estimated composition of the rock at the Venera 8 landing site is granodiorite or dacite and is geochemically similar to the Archean calc-alkaline silicic rocks from greenstone belts (Nikolayeva 1990; Shellnutt 2019). Moreover, visible and infrared thermal imaging spectrometry (VIRTIS) of Alpha Regio (tesserae) indicates the presence of low-Fe rocks suggesting either anorthositic cumulate rocks or plagioclase-rich tonalite can satisfy the emissivity signature (Gilmore et al. 2015). Furthermore, modeling suggests it is possible that surface water may have been present on Venus during the Archean and only disappeared within the last billion years or when the extreme CO_2 greenhouse developed (Way et al. 2016; Khawja et al. 2020). Therefore, it is entirely possible that sedimentary rocks were precipitated and deposited and hydrothermal metamorphism and mineralization occurred previously. Coupled with the compressional mountain features of Ishtar Terra and large volcanic rise of Beta Regio, it would appear that Venus, in the absence of plate tectonics, may be a near perfect analogue of pre-plate tectonics Earth (Harris and Bédard 2014; Hansen 2018; Wyman 2018).

In spite of the possible similarities from a macro perspective, there is significant debate on the exact composition of the tesserae, depositional processes, role of a hydrosphere, origin of coronae, the mantle thermal regime, and the tectonic regimes that were operating on ancient Earth and Venus. Recent investigations suggest that the tesserae could be composed of mafic volcanic–sedimentary sequences rather than intermediate to silicic rocks (Wroblewski et al. 2019; Byrne et al. 2021). Silicic rocks and anorthosite have not been positively identified and an argument can be made that the high U (2.2 ± 0.7 ppm), Th (6.5 ± 2.2 ppm), and K_2O (4.0 ± 1.2 wt.%) contents reported at the Venera 8 landing site could be lamprophyric (alkali basalt) rather than silicic (Basilevsky et al. 1992). It is possible that Venus had a hydrosphere during the Archean, but lithified sedimentary rocks (or their metamorphic equivalents) derived by mechanical weathering (sandstone, shale, greywacke, conglomerate) and chemical precipitation (limestone, evaporites, banded iron formation) have not been positively identified. The only possible evidence for the existence of S-rich evaporite rocks or material (gypsum, anhydrite, kieserite) is the high SO_3 (4.7 ± 1.5 wt.%) content measured at the Vega 2 landing site but whether the sulphur is from a sulphide (S^{2-}) or sulphate (SO_4^{2-}) is unknown. Given the possibility of an ocean, it would be expected that volcanogenic massive sulphide deposits would exist as shallow basaltic intrusions provide the heat engine to drive the circulation of hydrothermal cells that can transport metals. Corona structures, a common volcanic feature of Venus, do not appear to have a terrestrial analogue, although there are suggestions that a similar volcanic feature may exist (Lopez et al. 1997; Buchan and Ernst 2021). It is entirely possible that coronae existed on Earth and were a feature of Archean oceanic crust but were subducted prior to or during the Paleoproterozoic. The T_P estimates and the K/U and K/Th ratios indicate conditions, mantle compositions, and temperatures of cyclicity and decay similar to modern Earth (Taylor and McLennan 1986; Lee et al. 2009; Gillmannn and Tackley 2014; Ogawa and Yanagisawa 2014; Rubie et al. 2015; Weller and Duncan 2015; Shellnutt 2016; Walzer and Hendel 2017). However, the identification of volcanic features indicative of mantle plumes, plume swarms, and hotspot regimes appears to suggest that, of all the uncertainties, this could be the most similar to Archean Earth or a non-plate tectonic regime (Herrick et al. 2005; Basilevksy and Head 2007; Smrekar et al. 2010; Gülcher et al. 2020). Therefore, the tectonic regimes of Venus and Earth may have been similar during the earliest Archean, but diverged after the initiation of plate tectonics.

The initiation of modern (Phanerozoic) terrestrial plate tectonics is vociferously debated and there are advocates that suggest it may have always operated or that it began at ~ 3.2 Ga, ~ 2.5 Ga, ~ 1.0 Ga, or ~ 0.8 Ga (Condie and Kröner 2008; Stern 2008; Hamilton 2011, 2019; Dewey et al. 2021; Windley et al. 2021). This is a key argument for the comparison of Earth and Venus as it is clear that the two most recognizable physiographical features (mid-ocean ridge, subduction zones) attributed to plate tectonics are not present on Venus. The precise origin of granite–greenstone and granulite–gneiss belts is still debated and there are compelling arguments for and against the operation of plate tectonic-related processes in their development (de Wit and Ashwal 1995; Anhaeusser 2014; Thurston 2015). Nevertheless, it is clear that the generation of highly differentiated continental crust appears to have been absent, very slow, or stunted on Venus.

The continental crust represents ~ 41% of the Earth's surface area and ~ 0.7% of its volume. It has taken ~ 4.5 billion years to create the volume of continental crust but the rate of crustal growth across geological time is uncertain (Hawkesworth et al. 2019, 2020). The end-member models of crustal growth are rapid development followed by steady state, continuous growth, and continuous but episodic growth. The different models are illustrated in Figure 9. There are a number of uncertainties in the models but perhaps the most significant uncertainty is the timing of modern plate tectonics (Condie 2018; Windley et al. 2021). Assuming Venus was a perfect analogue to Earth and everything is proportionate (i.e. thermal structure, tectonic regimes) to the size difference of the planets then its surface should have a similar but lower absolute area and volume of continental crust as the Earth today. Clearly this is not the case as the tesserae, assuming they are similar to continental crust, represent ~ 7.3% of the surface area and 0.1% of the volume (Ivanov and Head 2011; James et al. 2013). If the surface areas of tesserae and continental crust are compared, then Venus developed only 17% of its total expected crust. If the volumes are compared then, depending on the thickness of the smaller tesserae, the amount reaches up to 20% of the expected crust. According to different terrestrial crustal growth models, the proportion of continental crust equaling 17% to 20% corresponds to three different potential age ranges (Fig. 9). The oldest age range is Hadean to Eoarchean (4.4 Ga to 3.9 Ga), the middle age range is Mesoarchean to Neoarchean (3.1 Ga to 2.7 Ga), and the youngest range is Paleoproterozoic (2.4 Ga to 2.1 Ga). Thus, it would seem that the geological processes of crustal evolution on Venus either operate at a significantly slower pace than Earth or they functionally stopped, possibly on or before the Paleoproterozoic (i.e. ≥ 2.1 Ga).

Is Venus analogous to Archean Earth? The answer appears to be maybe as there are some large scale motions and magma fluxes capable of resurfacing the planet with lava and moving small continental blocks that could be indicative of pre-plate tectonics Earth. However, the level of understanding of the crustal evolution of Venus is in its infancy and there is only a limited understanding of a possible Venusian hydrosphere. New geological observations and geochemical and isotopic surface measurements are needed to robustly evaluate the possibility that Venus and Earth evolved along similar paths during the Archean. Although it is possible that Venus and Early Earth may bear some resemblance there are too many uncertainties at the moment to provide a firm conclusion.

CONCLUSIONS

The basalt identified at the Venera 14 landing site is compositionally similar to tholeiitic basalt of terrestrial Archean greenstone belts. Primitive melt reconstruction (ultramafic) and petrological modeling of Venusian basalt shows that most of the tholeiitic and calc-alkaline volcanic (mafic, intermediate, silicic) and plutonic (granite, anorthosite, cumulate-layered mafic intrusions) rocks of a greenstone belt can be generated by conventional physio-chemical processes acting on these basaltic melts, such as low to medium (0.1 to 0.5 GPa) pressure

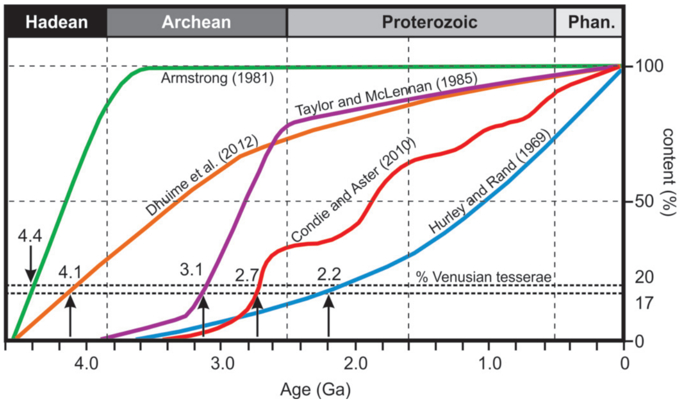

Figure 9. Crustal growth curves showing the models that constrain the volume of crust in the past independent of present day age distributions (Hurley and Rand 1969; Armstrong 1981; Taylor and McLennan 1985; Condie and Aster 2010; Dhuime et al. 2012).

fractional crystallization (intermediate, silicic), mineral accumulation (layered mafic intrusions, anorthosite), or high pressure (≥ 0.5 GPa) partial melting (tonalite–trondhjemite–granodiorite). The formation of clastic sedimentary rocks and chemically precipitated sedimentary rocks on Venus is uncertain and dependent on the existence of a paleohydrosphere. Consequently, it is possible that the crust of Venus could have produced the submarine igneous rock suites that typify terrestrial Archean greenstone belts. Although the present-day tectonic regimes of Venus and Earth are vastly different, it is possible that they were very similar until the moment that modern plate tectonics began on Earth or ended on Venus.

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