Appendix A: Mass balance calculations

Inclusion oxide phase does not have the same chemistry and appearance in all peridotites of the Zunhua belt, suggesting that the origin of this phase is different for different populations. On the basis of these observations, two main populations of inclusions recognized. Samples ZU02-04, ZU02-05, and ZU02-08 exist as blobs within the host grain, and contain significant amount of Fe, Cr, and Al., samples ZU02-01, ZU02-02, and ZU02-07 occur in grain cracks and rims only and are composed of magnetite with negligible Cr and Al. The difference in chemistry and distribution of the inclusion oxide phase suggest that the origin of this phase is different for each population. The Fe, Cr and Al rich blobs were likely exsolved from the host oxide phase and therefore are secondary. The Fe in magnetite cracks and rims was mobilized during the serpentinization of olivine grains, and therefore are likely to have been an original component of the source.

In order to determine the composition of the mantle, spinels must be extracted from the whole-rock XRF data. This includes host oxide phase from all seven peridotites, and inclusion oxide phases from samples ZU02-04, ZU02-05, and ZU02-08. In mass balance calculation, it was assumed that Archean mantle had an average Cr content of 0.43%, the average value for peridotites reported by Herzberg (1993). This chromium content is similar to those reported in other compilations (Maaloe and Aoki, 1977) and to fertile mantle peridotites (Sun and McDonough, 1995).

The mass fraction of X oxide added to the mantle was determined from the mass balance equation:

(1) $XRF_{C2O3}=X(C_{Cr2O3}^{oxide})+(1-X)(0.43)$

Where $XRF_{Cr2O3}=Cr_2O_3$ content of the Zunhua peridotites determined by whole rock XRF analysis; X=the mass fraction of the oxide phase; C=the weight percent concentration of Cr_2O_3 in the bulk oxide phase; and 0.43=the Cr_2O_3 content of average mantle peridotite (Herzberg, 1993).

Once the mass fraction of oxide X was determined, the composition of the Archean mantle was calculated for all other oxides with the mass balance equation:

(2) *Zunhua XRF=(1-X) (Archean mantle) + X(bulk oxide composition)*

The results of the mass fraction of oxide added to each peridotite sample are given in Table 6.

Table 1. Average mineral chemistry of Zunhua peridotites*

Sample	ZU02-01		ZU02-02		ZU02-04			ZU02-05			ZU02-07	
Mineral	Chl (n=10)	Serp (n=25)	Serp (n=20)		Serp (n=25)	Opx (n=25)	Amp (n=40)	Serp (n=15)	Amp (n=15)		Serp (n=20)	Cpx (n=30)
SiO_2	31.23	40.68	41.50		42.58	56.46	44.21	42.62	43.99		42.82	54.25
TiO_2	0.28	0.01	0.01		0.03	0.03	0.44	0.01	0.40		0.00	0.03
Al_2O_3	10.71	0.11	0.03		1.31	1.75	12.28	0.77	12.69		0.47	0.79
Cr_2O_3	0.42	0.19	0.04		0.13	0.20	1.10	0.01	1.13		0.06	0.20
FeO	7.89	2.46	1.19		2.60	6.75	4.82	2.58	4.97		2.10	2.11
MnO	0.02	0.03	0.01		0.05	0.19	0.10	0.02	0.07		0.07	0.09
MgO	32.39	39.84	40.26		36.82	33.30	18.05	38.26	17.79		38.68	17.25
CaO	0.01	0.03	0.02		0.21	0.26	11.90	0.03	11.89		0.04	24.46
Na_2O	0.01	0.01	0.01		0.00	0.03	2.25	0.00	2.40		0.03	0.15
K_2O	0.36	0.00	0.00		0.01	0.01	0.33	0.01	0.38		0.01	0.01
NiO	0.142	0.375	0.178		0.273	0.069	0.101	0.258	0.090		0.187	0.032
H_2O	16.53	16.27	16.77		15.99	0.00	4.42	15.43	4.21		15.53	0.00
Total	100.00	100.00	100.00		100.00	99.04	100.00	100.00	100.00		100.00	99.34
Mg#[1]	87.9	96.7	98.40		96.2	89.8	87.0	97.0	86.5		97.0	93.6
Spinel	Host (n=25)	RC (n=10)	Host (n=25)	RC (n=25)	Host (n=50)	Inc (n=50)	Bulk	Host (n=25)	Inc (n=25)	Bulk	Host (n=40)	RC (n=10)
SiO_2	0.008	0.074	0.01	0.045	0.004	0.053	0.013	0.002	0.032	0.010	0	0.117
TiO_2	0.36	0.04	0.32	0.06	0.18	0.80	0.29	0.19	0.78	0.35	0.33	0.09
Al_2O_3	12.94	0.01	12.76	0.02	32.58	3.32	27.04	30.97	4.03	23.56	13.94	0.96
Cr_2O_3	40.47	1.55	42.87	3.07	27.35	17.70	25.51	27.49	18.14	24.92	34.34	3.70
FeO_T	40.00	97.98	38.24	96.32	28.72	74.41	37.33	31.15	73.78	42.88	45.29	94.27
MnO	0.46	0.05	0.43	0.09	0.34	1.61	0.58	0.35	1.21	0.59	0.51	0.28
MgO	5.66	0.12	5.24	0.15	10.56	1.18	8.78	9.58	1.25	7.29	5.30	0.40
NiO	0.128	0.175	0.101	0.235	0.273	0.931	0.397	0.263	0.788	0.407	0.263	0.181
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100	100
Si	0.000	0.003	0.000	0.002	0.000	0.002	0.000	0.000	0.001	0.000	0.000	0.004
Ti	0.009	0.001	0.008	0.002	0.004	0.021	0.007	0.004	0.021	0.008	0.008	0.002
Al	0.509	0.001	0.505	0.001	1.148	0.139	0.982	1.104	0.168	0.874	0.546	0.040
Cr	1.068	0.044	1.137	0.087	0.644	0.496	0.621	0.657	0.507	0.620	0.903	0.104
Fe^{3+}	0.414	1.952	0.350	1.909	0.204	1.342	0.390	0.235	1.304	0.497	0.543	1.849
Fe^{2+}	0.702	0.987	0.723	0.982	0.514	0.863	0.572	0.553	0.876	0.632	0.716	0.965
Mn	0.013	0.001	0.012	0.003	0.009	0.048	0.015	0.009	0.036	0.016	0.014	0.009
Mg	0.282	0.006	0.262	0.008	0.47	0.062	0.403	0.432	0.066	0.342	0.263	0.021
Ni	0.000	0.005	0.000	0.007	0.007	0.027	0.010	0.006	0.022	0.010	0.007	0.000
Mg#[2]	28.6	0.6	26.6	0.8	47.8	6.7	41.3	43.9	7.0	35.1	26.9	2.2
Cr#	67.7	98.9	69.3	98.9	36.0	78.1	38.8	37.3	75.2	41.5	62.3	72.1

*Chl: chlorite; Serp: serpentine; Opx: orthopyroxene; Cpx: clinopyroxene; Amp: amphibole; Inc: Inclusion; RC: Rim - Crack

n = number of analyses; Fe_2O_3 and FeO in spinel calculated from stoichiometry. Mg#1 = 100(MgO+FeOT); Mg#2 = 100(MgO+FeO) (molar)

Table 1. Continues

Sample	ZU02-08				ZU02-14		
Mineral	Serp (n=10)	Opx (n=37)	Cpx (n=25)	Amp (n=25)	Serp (n=10)	Cpx (n=25)	Amp (n=25)
SiO_2	40.86	56.42	54.69	46.30	42.51	54.03	49.54
TiO_2	0.01	0.02	0.02	0.15	0.01	0.06	0.16
Al_2O_3	0.35	1.21	0.92	9.50	0.89	1.63	8.21
Cr_2O_3	0.01	0.16	0.19	1.01	0.04	0.13	0.52
FeO	2.02	7.51	2.29	4.37	2.40	2.60	4.81
MnO	0.06	0.21	0.09	0.07	0.06	0.09	0.22
MgO	39.15	33.77	17.60	18.82	39.87	17.26	19.35
CaO	0.03	0.29	24.03	12.21	0.02	24.37	12.06
Na_2O	0.01	0.02	0.13	1.48	0.01	0.05	0.55
K_2O	0.01	0.00	0.00	0.31	0.00	0.00	0.43
NiO	0.177	0.055	0.035	0.083	0.125	0.037	0.091
H_2O	17.33	0.00	0.00	5.70	14.07	0	4.06
Total	100.00	99.67	100.00	100.00	100.00	100.26	100.00
Mg#	97.2	88.9	93.2	88.5	96.7	92.2	87.8

Spinel	Host (n=25)	Inc (n=15)	Bulk	Host (n=25)
SiO_2	0.006	0.033	0.011	0.019
TiO_2	0.30	0.31	0.3	0.77
Al_2O_3	15.45	2.96	14.75	3.36
Cr_2O_3	31.06	16.01	30.23	13.05
FeO	46.25	77.36	47.99	79.95
MnO	0.48	0.60	0.49	0.48
MgO	6.15	1.72	5.9	1.91
NiO	0.306	0.678	0.327	0.463
Total	100	100		100.00
Si	0.000	0.001	0.000	0.000
Ti	0.007	0.008	0.007	0.021
Al	0.597	0.124	0.572	0.142
Cr	0.805	0.448	0.787	0.369
Fe^{3+}	0.590	1.419	0.633	1.468
Fe^{2+}	0.678	0.872	0.688	0.924
Mn	0.013	0.018	0.014	0.015
Mg	0.3	0.091	0.290	0.049
Ni	0.008	0.019	0.009	0.013
Mg#	30.7	9.4	29.6	0.25
Cr#	57.4	94.6	57.9	72.3

Table 2. Average mineralogical composition of the Wutaishan dunites*.

Sample	2002-88			2002-89			2002-90			2002-91			
Mineral	Ol (n=21)	Serp (n=24)	Chl (n=16)	Ol (n=20)	Chl (n=25)	Amp (n=6)	Ol (n=39)	Serp (n=20)	Amp (n=20)	Ol (n=20)	Serp (n=3)	Chl (n=12)	Amp (n=10)
SiO_2	42.32	42.61	31.79	41.15	33.73	56.620	40.95	43.64	57.98	40.84	43.20	32.37	57.64
TiO_2	0.02	0.03	0.06	0.02	0.05	0.100	0.01	0.03	0.12	0.01	0.04	0.06	0.13
Al_2O_3	0.00	0.11	15.96	0.00	12.60	0.440	0.00	0.06	0.45	0.00	0.16	14.35	0.82
Cr_2O_3	0.01	0.02	1.40	0.01	1.16	0.050	0.01	0.01	0.03	0.01	0.01	1.42	0.08
FeO_T	4.39	2.02	2.57	4.56	2.63	1.220	6.03	1.41	1.40	5.38	1.36	2.63	1.52
MnO	0.11	0.06	0.01	0.10	0.02	0.050	0.11	0.03	0.06	0.15	0.04	0.02	0.07
MgO	53.34	38.37	30.30	54.09	34.60	22.910	53.06	40.95	24.19	53.05	40.50	33.56	23.85
CaO	0.02	0.04	0.02	0.00	0.08	16.140	0.01	0.08	12.95	0.01	0.01	0.01	12.60
Na_2O	0.01	0.02	0.02	0.00	0.01	0.100	0.01	0.01	0.09	0.02	0.02	0.02	0.20
K_2O	0.00	0.02	0.02	0.00	0.00	0.020	0.00	0.00	0.00	0.00	0.00	0.01	0.01
NiO	0.362	0.057	0.208	0.408	0.239	0.082	0.122	0.041	0.059	0.369	0.042	0.223	0.084
H_2O	0.00	16.64	17.64	0.00	14.88	2.268	0.00	13.74	2.68	0.00	14.62	15.33	2.99
Total	100.60	100.00	100.00	100.34	100.00	100.00	100.32	100.00	100.00	99.85	100.00	100.00	100.00
Mg#	95.6 (1.3)	97.1	95.5	95.5 (1.4)	95.9	97.1	94.0 (0.8)	98.1	96.9	94.6 (1.1)	98.2	95.8	96.5

Mineral	Mag (n=25)	Mag (n=15)	Mag (n=10)	Mag (n=10)
SiO_2	0.035	0.068	0.22	0.19
TiO_2	0.45	0.29	0.04	0.30
Al_2O_3	0.04	0.03	0.00	0.03
Cr_2O_3	7.79	5.65	0.21	6.15
FeO_T	88.80	90.40	96.64	88.75
MnO	0.57	0.29	0.11	0.62
MgO	2.00	2.39	2.20	2.94
NiO	0.234	0.865	0.484	0.684
Total	100	100	100.00	100.00
Mg#	10.8	13.0	11.7	16.1
Cr#	99.2	99.1	97.2	99.2

*Ol: olivine; Serp: serpentine; chl: chlorite; Amp: amphibole; Mag: magnetite

Mg# = 100(MgO+FeO) molar (1σ)

Table 3. Average compositions of podiform chromites

	Chromite pods				Small Chromite grains	
	ZZ-45 (n=25)	CM 10-1 (n=25)	1692 (n=25)	ZZ-56 (n=25)	ZZ-45 (n=15)	CM 10-1 (n=10)
SiO_2	0.095	0.038	0.025	0.007	0.019	0.018
TiO_2	0.14	0.15	0.12	0.124	0.144	0.14
Al_2O_3	5.34	5.60	5.93	6.55	5.72	5.44
Cr_2O_3	60.66	62.92	57.13	63.83	56.68	60.97
FeO_T	22.85	19.47	29.31	15.82	32.64	25.16
MnO	0.36	0.33	0.37	0.25	0.47	0.40
MgO	10.40	11.45	6.89	13.27	4.20	7.76
NiO	0.111	0.076	0.241	0.110	0.083	0.064
Total	100.0	100.0	100.0	100.0	100.0	100.0
Si	0.003	0.001	0.001	0.000	0.001	0.001
Ti	0.003	0.004	0.003	0.003	0.004	0.004
Al	0.211	0.22	0.24	0.253	0.236	0.219
Cr	1.608	1.655	1.548	1.653	1.569	1.648
Fe^{3+}	0.174	0.121	0.209	0.091	0.191	0.128
Fe^{2+}	0.467	0.421	0.631	0.343	0.764	0.591
Mn	0.010	0.009	0.011	0.007	0.014	0.012
Mg	0.520	0.568	0.352	0.648	0.219	0.396
Ni	0.003	0.002	0.007	0.003	0.002	0.002
Mg#	0.527	0.574	0.358	0.654	0.223	0.401
Cr#	0.884	0.883	0.866	0.867	0.869	0.883

Table 4. Major and trace element concentrations for ultramafic intrusions, pyroxenites, and amphibolites in the Zunhua ophiolitic belt.

	Peridotites							Pyroxenite	Amphibolites			
Samples	ZU02-01	ZU02-02	ZU02-04	ZU02-05	ZU02-07	ZU02-08	ZU02-14	ZU02-15	ZU02-19	ZU02-20	ZU02-21*	ZU02-22*
SiO_2	43.77	41.17	40.82	41.34	44.62	43.97	44.52	54.44	50.70	51.27	54.21	58.94
TiO_2	0.06	0.07	0.17	0.13	0.06	0.07	0.09	0.11	0.40	0.44	0.23	0.10
Al_2O_3	1.39	1.34	5.83	4.70	2.08	2.98	2.38	2.27	6.96	6.80	3.39	2.27
Fe_2O_3	12.90	15.95	13.88	13.81	11.14	11.76	11.90	4.99	10.00	10.04	13.54	8.75
MnO	0.09	0.08	0.18	0.18	0.13	0.12	0.16	0.13	0.17	0.15	0.23	0.14
MgO	41.55	40.44	37.32	38.81	39.11	37.90	37.92	18.69	19.70	19.13	20.41	24.80
CaO	0.10	0.81	1.48	0.85	2.70	2.96	2.87	18.90	10.37	10.53	7.24	4.82
K_2O	0.11	0.12	0.09	0.07	0.08	0.08	0.11	0.10	0.67	0.56	0.55	0.07
Na_2O	0.01	0.01	0.19	0.10	0.08	0.15	0.02	0.35	0.81	0.87	0.20	0.09
P_2O_5	0.01	0.01	0.02	0.01	0.01	0.01	0.04	0.01	0.23	0.19	0.01	0.01
LOI	12.48	12.35	10.43	11.10	10.92	10.68	10.94	1.27	1.94	1.68	2.88	3.90
Mg#	86.4	83.4	84.2	84.8	87.4	86.5	86.3	88.1	79.6	79.0	74.9	84.9
Cr	22325	23467	28374	22632	16292	19232	5302	3326	2973	2506	3559	4776
Co	130	142	160	151	131	138	123	37	65	63	59	64
Ni	3294	2335	2642	2130	1943	1825	1455	n.d.	869	796	747	1064
Cu	4.04	3.82	6.65	3.71	4.15	7.25	2.30	4.78	2.13	10.60	18.34	0.87
Zn	99	84	111	93	54	66	61	47	87	78	143	117
Pb	1.37	1.05	1.58	1.87	1.72	1.85	1.48	12.20	2.78	3.45	2.25	0.68
Rb	1.1	1.0	1.6	1.2	1.5	1.2	4.7	2.03	15.8	8.1	14.7	0.9
Sr	5	9	32	19	17	23	46	110	162	181	32	21
Ba	112	12	36	100	76	53	87	7	79	268	142	8
V	61	71	138	103	77	96	40	40	138	129	83	42
Nb	0.103	0.099	0.395	0.361	0.131	0.199	0.224	0.06	2.40	2.38	1.65	0.72
Ta	0.009	0.011	0.030	0.028	0.009	0.013	0.026	0.15	0.15	0.15	0.13	0.07
Zr	1.61	1.99	7.45	7.50	3.16	5.00	9.26	10.31	49.38	55.11	238.7	42.6
Hf	0.05	0.06	0.24	0.24	0.09	0.15	0.26	0.34	1.49	1.58	n.d.	n.d.
Th	0.12	0.13	0.24	0.23	0.16	0.20	0.91	0.51	2.18	1.61	0.38	0.37
U	0.03	0.22	0.04	0.05	0.04	0.06	0.13	0.08	0.27	0.20	0.06	0.01
Y	0.66	0.46	2.36	1.87	0.97	1.27	1.21	2.04	10.7	9.4	12.0	3.5
La	1.10	0.58	1.52	1.21	0.59	0.82	1.89	1.50	11.77	11.13	4.50	1.86
Ce	2.35	1.12	3.50	2.79	1.26	1.82	4.49	3.88	28.54	26.56	15.46	5.68
Pr	0.30	0.14	0.46	0.37	0.16	0.24	0.56	0.55	3.50	3.31	2.46	0.83
Nd	1.16	0.51	2.01	1.58	0.66	0.99	2.28	2.66	13.88	13.24	11.35	3.59
Sm	0.25	0.13	0.48	0.38	0.17	0.23	0.51	0.73	2.91	2.66	2.64	0.78
Eu	0.06	0.04	0.14	0.12	0.05	0.08	0.12	0.20	0.77	0.69	0.40	0.15
Gd	0.17	0.08	0.47	0.39	0.16	0.22	0.36	0.63	2.53	2.37	2.46	0.73
Tb	0.03	0.02	0.07	0.06	0.03	0.04	0.05	0.08	0.38	0.33	0.38	0.11
Dy	0.14	0.09	0.44	0.35	0.18	0.23	0.23	0.45	2.05	1.84	2.20	0.62
Ho	0.02	0.02	0.09	0.07	0.04	0.05	0.05	0.08	0.40	0.35	0.44	0.12
Er	0.07	0.05	0.27	0.21	0.12	0.15	0.13	0.23	1.16	1.02	1.30	0.36
Tm	0.01	0.01	0.04	0.03	0.02	0.02	0.02	0.03	0.16	0.14	0.19	0.05
Yb	0.06	0.05	0.25	0.20	0.11	0.16	0.12	0.18	1.05	0.91	1.28	0.36
Lu	0.02	0.01	0.05	0.03	0.02	0.03	0.03	0.03	0.17	0.15	0.18	0.05
$(La/Yb)_{cn}$	12.13	7.76	4.42	4.40	3.83	3.73	11.03	6.00	8.04	8.73	2.52	3.68
$(La/Sm)_{cn}$	2.87	2.86	2.06	2.09	2.18	2.30	2.38	1.32	2.61	2.70	1.10	1.54
$(Gd/Yb)_{cn}$	2.17	1.30	1.57	1.62	1.23	1.17	2.40	2.91	1.99	2.15	1.59	1.67
$(Eu/Eu^*)_{cn}$	0.95	1.09	0.89	0.93	0.93	1.07	0.89	0.89	0.87	0.84	0.48	0.61
$(Ce/Ce^*)_{cn}$	1.01	0.98	1.03	1.02	1.00	1.01	1.07	1.05	1.09	1.07	1.14	1.12
AL_2O_3/TiO_2	24	19	34	38	37	44	27	20	17	15	15	22
Zr/Hf	33.1	34.5	30.6	31.6	33.5	32.9	35.3	30.1	33.1	35.0		
Nb/Ta	11.6	9.0	13.1	12.9	14.0	15.6	8.5	5.6	17.1	16.5	12.6	10.7
Zr/Y	2.4	4.3	3.2	4.0	3.2	3.9	7.7	5.0	4.6	5.9	19.9	12.0
Ti/Zr	213	209	137	100	106	81	58	66	49	48	6	15
Nb/Nb*	0.10	0.13	0.24	0.25	0.15	0.18	0.06	0.03	0.17	0.20	0.46	0.31
Zr/Zr*	0.21	0.54	0.53	0.68	0.65	0.73	0.60	0.51	0.53	0.64	3.04	1.78
Hf/Hf*	0.23	0.57	0.63	0.78	0.70	0.81	0.62	0.61	0.58	0.66		
Ti/Ti*	0.69	1.63	0.89	0.81	0.82	0.73	0.51	0.41	0.37	0.43	0.22	0.34
Northing	40°13.591'	40°113.591'	40°14.596	40°14.596	40°14.531	40°14.531	40°14.244	40°14.244	40°22.538	40°22.548	40°22.538	40°22.538
Easting	118°00.584	118°00.584	118°04.790	118°04.790	118°04.798	118°04.798	113°03.669	113°03.669	118°29.017	118°29.017	118°29.027	118°29.027

*Variably altered samples

Table 5. Lu-Hf isotope data for the Zunhua peridotites

	$^{176}Lu/^{177}Hf$	Lu (ppm)	$^{176}Hf/^{177}Hf$	Hf (ppm)	ε_{Hf} (2547 Ma)
ZU02-01	0.0319	0.0098	0.282932±21	0.04342	7.9
ZU02-04	0.0244	0.0379	0.282570±08	0.2205	8.1
ZU02-04d	0.0243	0.0378	0.282580±11	0.2205	8.5
ZU02-05	0.0208	0.0313	0.282429±12	0.2136	9.3
ZU02-07	0.0307	0.0183	0.282921±12	0.0844	9.5
ZU02-08	0.0249	0.0242	0.282603±19	0.1375	8.3
ZU02-08d	0.0248	0.0241	0.282621±14	0.1378	9.2
ZU02-13	0.0131	0.0146	0.282085±29	0.1580	10.4
ZU02-14	0.0114	0.0190	0.281937±19	0.2366	8.1
ZU02-15	0.0155	0.0370	0.282155±11	0.3386	8.7

Table 6. Model compositions of the Archean mantle calculated from the Zunhua peridotites

	ZU02-01	ZU02-02	ZU02-04	ZU02-05	ZU02-07	ZU02-08	ZU02-14
SiO_2	45.99	43.34	45.37	45.44	45.98	45.91	45.33
TiO_2	0.04	0.05	0.15	0.09	0.05	0.06	0.08
Al_2O_3	0.50	0.46	2.77	2.33	1.62	2.31	2.38
Cr_2O_3	0.43	0.43	0.43	0.43	0.43	0.43	0.43
FeO	9.23	12.28	8.76	8.50	8.61	8.45	9.82
MnO	0.06	0.05	0.13	0.13	0.12	0.10	0.16
MgO	43.23	42.19	40.28	41.77	40.10	39.26	38.58
CaO	0.11	0.85	1.64	0.94	2.78	3.09	2.92
Na_2O	0.00	0.00	0.22	0.11	0.08	0.15	0.02
K_2O	0.12	0.12	0.10	0.08	0.08	0.08	0.11
P_2O_5	0.00	0.01	0.02	0.01	0.00	0.00	0.04
NiO	0.281	0.197	0.173	0.164	0.156	0.151	0.125
Spinel mass fraction added	0.0689	0.0690	0.1208	0.1074	0.0365	0.0513	0.0135