Alaskan-type mafic–ultramafic complex at Padhar, Betul Belt, Central India

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We report here an Alaskan-type mafic–ultramafic complex at Padhar from the Precambrian Betul Belt of Central India. The Padhar intrusive bodies show lithological zoning defined by olivine-bearing ultramafic rocks in the core and gabbroic rocks at the margins, and are commonly accompanied by Cr–Cu–Ni sulphide mineralization. Mineral chemistry and whole-rock geochemistry of these rocks indicate that they are derived from the crystallization of hydrous magmas. The Padhar complex is characterized by high Mg and low abundance of incompatible trace elements. Flat REE pattern with negative Nb anomaly suggests arc-magmatism typical of Ural–Alaskan type. Presence of Mg-rich clinopyroxene and hornblende-rich rock types in the Padhar mafic–ultramafic intrusives along with paucity of orthopyroxenes in them further distinguish its from different types of complexes, i.e. ophiolite, Alpine and stratiform layered-type. These features are akin to Alaskan-type rocks as seen in Alaska, Canada and Urals of Russia. This finding of Alaskan-type ultramafic complex in the Padhar area of Betul Belt, Madhya Pradesh, is significant and has important implications in the tectonics and geodynamics of the Central Indian Tectonic Zone in general, and in the search of platinum group of minerals in particular.

Keywords: CITZ, mafic–ultramafic complex, hydrous magmas, intrusive bodies, lithological zoning.

ALASKAN complexes are a special category of ultramafic–mafic intrusive bodies, which have attracted the attention of modern geoscientists because they host economic deposits of precious metals, mainly platinum, and represent a puzzling geological feature due to their unusual petrologic affinity and distinctive igneous tectonic setting[1–3]. In 1960, Alaskan-type complexes were recognized for the first time as a separate class of plutonic intrusive bodies considering their distinct internal structure, tectonic setting, composition and mineralization[4]. They are generally characterized by their small size, rounded to elliptical shape, having core of dunite enveloped by successive zones of wehrlite, olivine clinopyroxenite, hornblende clinopyroxenite and hornblende gabbro from core to rim.

In most of the complexes, it is rare to find a complete sequence of lithologies due to discontinuous, asymmetrical or incomplete zoning[1,2]. Mineralogically, these are dominated by olivine, clinopyroxene and hornblende with minor chromite, ilmenite and magnetite. Orthopyroxene and plagioclase are rare, except in a few areas such as Karayasmak complex, NE Turkey[1]. In addition to the type locality of Alaska, similar intrusions have been documented at modern and ancient subduction settings worldwide – in Eastern Pontides, Turkey[1], Eastern Desert, Egypt[5], British Columbia[6]; Venezuela[7]; New South Wales, Australia[8]; Southland, New Zealand[9]; the Ural Mountains[10]; the Koryak Highland, Northern Kamchatka, Russia[11]; NW China[12]; Superior Province, Canada[13].

The intrusive Padhar mafic–ultramafic complex (PMUC) is known to occur as dismembered bodies of varied dimensions in the Betul Belt Central Indian Tectonic Zone (CITZ), hitherto considered as layered igneous complex[14]. The rock formations of the complex were recently characterized in some detail, which showed that they may not be rocks layered igneous complex, but it bears some unusual type[15] signature. The present study reveals that the characters are more akin to Alaskan-type mafic–ultramafic complex setup.

In fact, Alaskan-type ultramafic complexes have rarely been reported from India. There is only a recent record from the North Purilia shear zone of Singbhum craton[16]. Therefore, finding of such complex in Central India has significant implications in our understanding of tectonics of CITZ. In most Ural–Alaskan-type complexes, petrological and mineralogical similarities have been widely accepted as identification criteria[17]. Here we report an Alaskan-type mafic–ultramafic complex at Padhar based on field geology, mineralogy and preliminary geochemistry.

The PMUC is an integral part of the Meso–Proterozoic Betul supracrustal belt in CITZ, situated in the western and northwestern parts of the Belt covering about 160 sq. km area[18,19] (Figure 1). Large intrusive bodies of unaltered olivine websterite, clinopyroxenite, hornblendite, gabbro, diorite and foliated ultramafic rocks, viz. serpentinite, talc-antigorite schist and chlorite schist are exposed around Padhar, Gajpur, Jakhli, Jharkund and several other places in the Betul Belt. They have been collectively designated as the PMUC. Apart from the main Padhar complex, there are also smaller mappable units of gabbro, pyroxenite and hornblendite in association with bimodal volcanics in the Betul belt (Figure 2 *a* and *b*). PMUC is a well-differentiated complex and contains mainly mafic rocks in the southern and northern parts. The ultramafic rocks are mostly seen in the central part of the intrusion and some of them are lenticular in shape surrounded by mafic rocks (Figure 1)[20].

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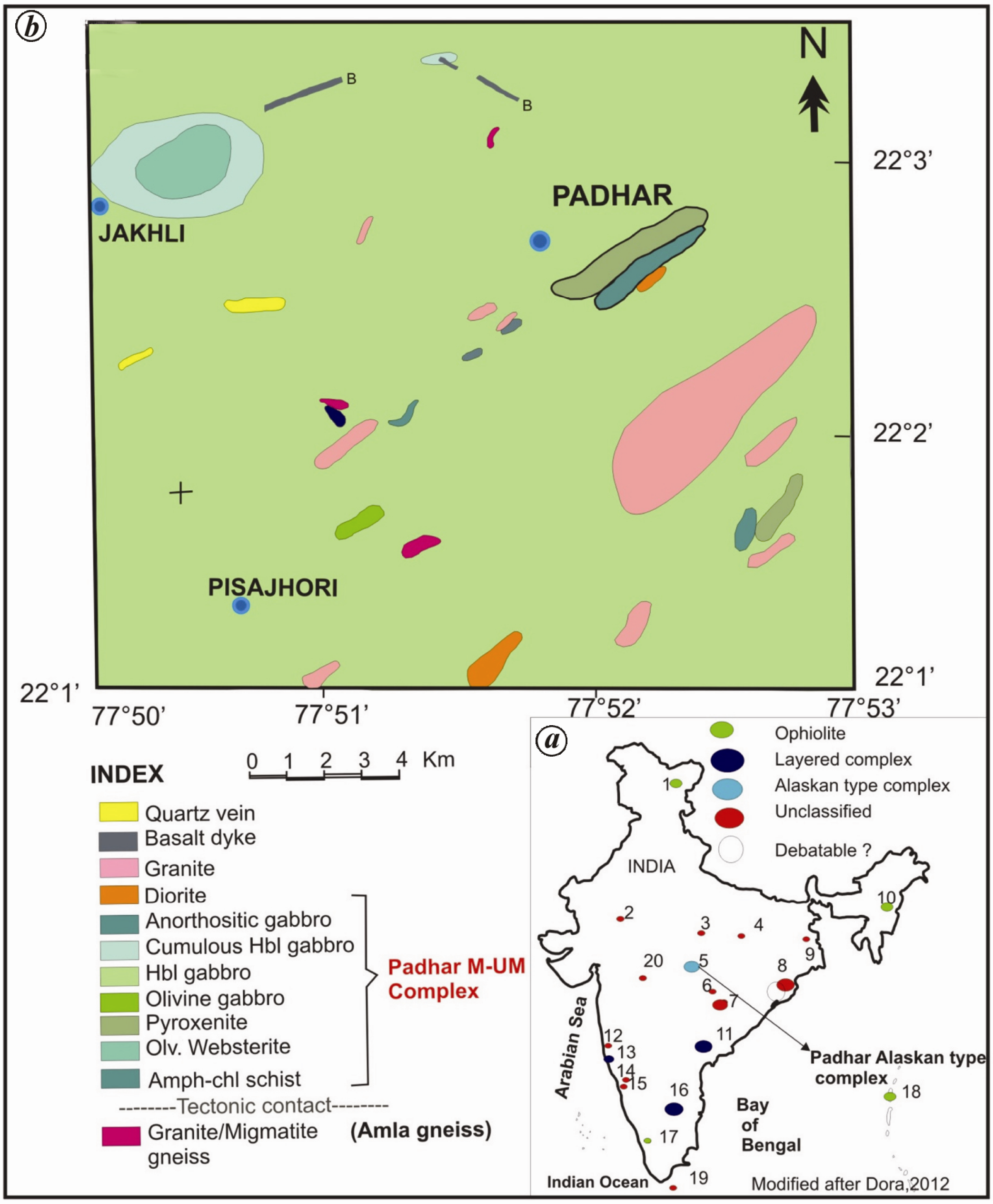

Figure 1. ***a***, India map showing the location of Padhar mafic–ultramafic complex and other location of mafic–ultramafics of India[32]. ***b***, Geological map of the Padhar mafic–ultramafic complex, Betul Belt, Central Indian Tectonic Zone.

Petrographic study of ultramafic rocks reveals the presence of olivine, clinopyroxene, minor orthopyroxene and phlogopite as essential phases with plagioclase, magnetite and chromite as accessories (Figure 2 *c*). The mafic rocks are dark greenish-grey, medium-grained gabbros and hornblende gabbros, characterized by subophitic and hypidiomorphic textures with subhedral plagioclase laths partially enclosed in magnesio-hornblende or rarely in clinopyroxene. Accessories include biotite, Fe-chromite and magnetite. Dissemination of sulphides, viz. pyrite, pyrrhotite, pentlandite and chalcopyrite is seen in the intergranular spaces. Pentlandite shows flame-like exsolution texture (Figure 2 *d*). Gold and iridium-bearing platinum group mineral (PGM) is identified by SEM as inclusions in chromite (Figure 2 *e* and *f*). Detailed ore petrology of the sulphide and oxide phases is a subject matter of another study.

Chemical composition of silicate, oxide and sulphide minerals was determined using electron probe micro analyzer (EPMA; Cameca SX-100 model) at Geological Survey of India, Bengaluru. The analyses were carried out at 15 kV–15 nA and 20 kV–20 nA with counting time of 10

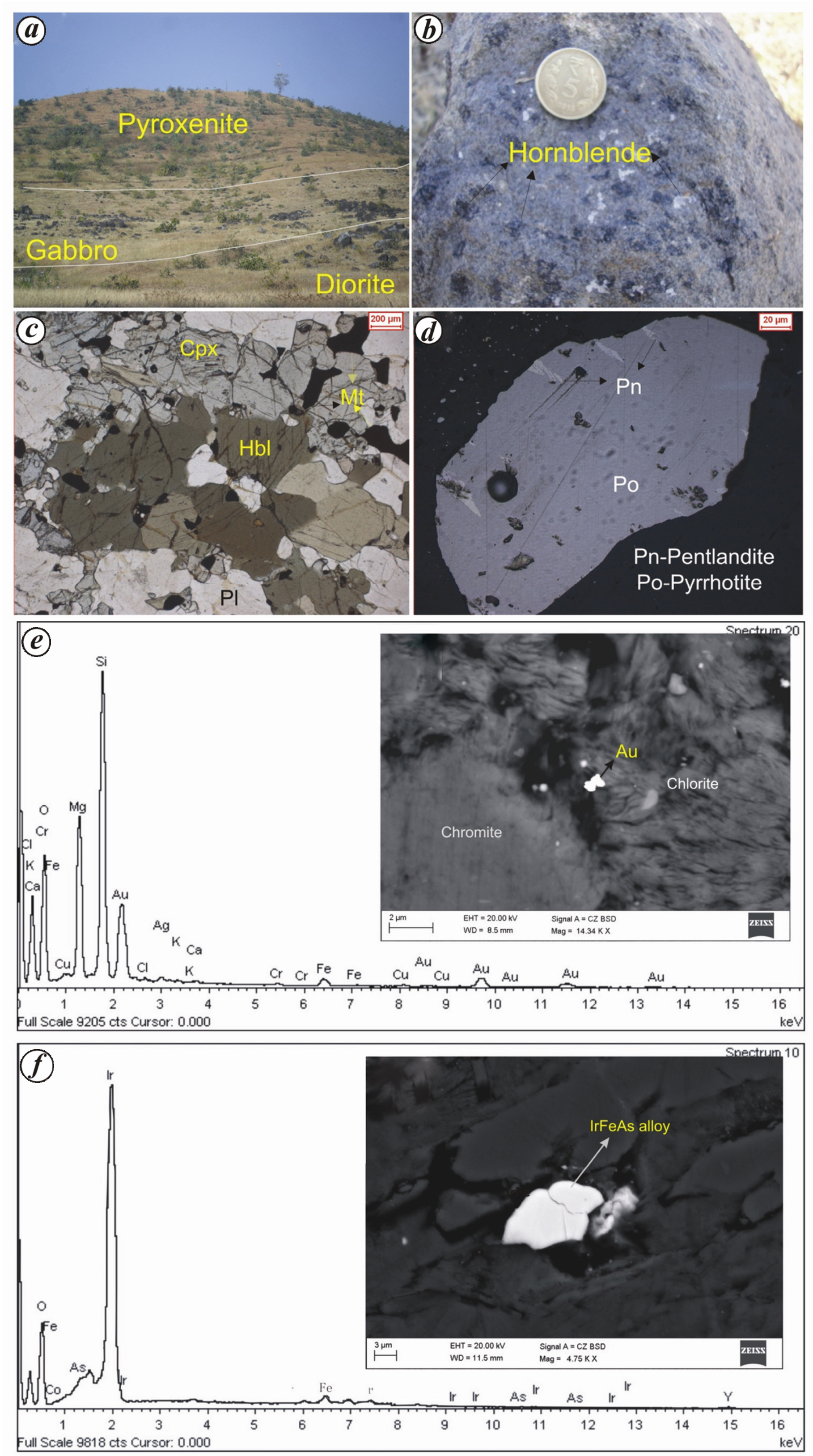

Figure 2. ***a***, ***b***, Field photographs showing (***a***) sequential occurrence of pyroxenite, gabbro and diorite at Padhar hill and (***b***) cumulate characters of hornblende gabbro. ***c***, ***d***, Photomicrographs of (***c***) hornblende gabbro showing cumulate texture, and (***d***) pentlandite showing flame-like exsolution texture in pyrrhotite. (***e***) SEM images of chrome spinel showing bright and high reflectance platinum group mineral and gold grains (***f***) along with EDS spectra.

Table 1. Representative mineral chemistry of Cpx and Cr-spinel from Padhar mafic–ultramafic complex, Betul Belt, Madhya Pradesh (MP), India

Sample	PDH1		Fe17		Fe8			Fe-18						
Rock name	Ol websterite		Pyroxenite		Gabbro variants			Talc-Chl-serpentine schist						
SiO_2	51.67	52.44	52.64	52.45	53.34	53	52.76	0.07	0.01	0.07	0.01	0.01	0.09	0.02
TiO_2	0.29	0.22	0.28	0.53	0.12	0.1	0.12	0.55	0.51	0.55	0.51	0.35	0.3	0.52
Al_2O_3	1.45	1.38	1.95	2.24	1.63	1.63	1.41	0.33	0.29	0.33	0.29	0.43	0.12	0.26
Cr_2O_3	0.13	0.1	0.08	0.2	0.11	0.1	0.16	21.35	23.18	21.35	23.18	26.54	21.07	25.96
FeO	4.42	5.1	5.82	5.42	5.82	5.9	5.73	72.97	70.49	72.97	70.49	68.53	73.41	68.33
MnO	0.12	0.23	0.12	0.11	0.14	0.23	0.19	0.66	0.79	0.66	0.79	0.89	0.63	0.87
MgO	15.9	16	14.9	14.84	15.23	15.09	15.36	0.09	0.09	0.09	0.09	0.05	0.08	0.09
CaO	24.69	24.16	24.96	24.69	24.26	24.69	24.63	0.02	0	0.02	0	0	0	0
Na_2O	0.35	0.29	0.45	0.47	0.32	0.38	0.32	0	0	0	0	0.02	0.05	0
K_2O	0	0.01	0.01	0	0	0.02	0	0.01	0	0.01	0	0.01	0	0
Total	99.06	100.09	101.27	100.99	100.98	101.18	100.83	96.05	95.36	96.05	95.36	96.83	95.75	96.05
O	6	6	6	6	6	6	6	4	4	4	4	4	4	4
Si	1.928	1.939	1.930	1.924	1.953	1.944	1.943	0.003	0	0.003	0	0	0.004	0.001
Ti	0.008	0.006	0.008	0.015	0.003	0.003	0.003	0.019	0.017	0.019	0.017	0.012	0.01	0.017
Al	0.064	0.060	0.084	0.097	0.070	0.070	0.061	0.018	0.015	0.018	0.015	0.022	0.006	0.014
Cr	0.004	0.003	0.002	0.006	0.003	0.003	0.005	0.762	0.828	0.762	0.828	0.923	0.758	0.911
Fe	0.138	0.158	0.179	0.166	0.178	0.181	0.176	2.755	2.663	2.755	2.663	2.521	2.793	2.537
Mn	0.004	0.007	0.004	0.003	0.004	0.007	0.006	0.025	0.03	0.025	0.03	0.033	0.024	0.033
Mg	0.884	0.882	0.814	0.811	0.831	0.825	0.843	0.006	0.006	0.006	0.006	0.003	0.005	0.006
Ca	0.987	0.957	0.981	0.971	0.952	0.970	0.972	0.001	0	0.001	0	0	0	0
Na	0.025	0.021	0.032	0.033	0.023	0.027	0.023	0	0	0	0	0.002	0.004	0
Total cation	4.043	4.034	4.035	4.027	4.018	4.031	4.032	3.589	3.561	3.589	3.561	3.517	3.606	3.519
Fe^{3+}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.199	1.139	1.199	1.139	1.043	1.221	1.057
Fe^{2+}	0.138	0.158	0.179	0.166	0.178	0.181	0.176	1.556	1.524	1.556	1.524	1.478	1.572	1.481
Fe^{3+}/Fe^{2+}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.77	0.747	0.77	0.747	0.706	0.777	0.714
Fe^{3+}/FeT	0.000	0.000	0.000	0.000	0.000	0.000	0.000							
XMg*	0.865	0.848	0.820	0.830	0.823	0.820	0.827	0.002	0.002	0.002	0.002	0.001	0.002	0.002
XMg	0.865	0.848	0.820	0.830	0.823	0.820	0.827	0.004	0.004	0.004	0.004	0.002	0.003	0.004
Fs	0.068	0.078	0.089	0.084	0.090	0.090	0.088							
En	0.435	0.437	0.406	0.409	0.419	0.412	0.419							
Wo	0.485	0.474	0.489	0.490	0.480	0.484	0.483							
Jh	0.002	0.004	0.002	0.002	0.002	0.004	0.003							
XMn	0.002	0.004	0.002	0.002	0.002	0.004	0.003							
YCr								0.385	0.418	0.385	0.418	0.464	0.382	0.46
YAl								0.009	0.008	0.009	0.008	0.011	0.003	0.007
YFe_3								0.606	0.575	0.606	0.575	0.525	0.615	0.533
$Cr^{\#}$								0.977	0.982	0.977	0.982	0.976	0.992	0.985

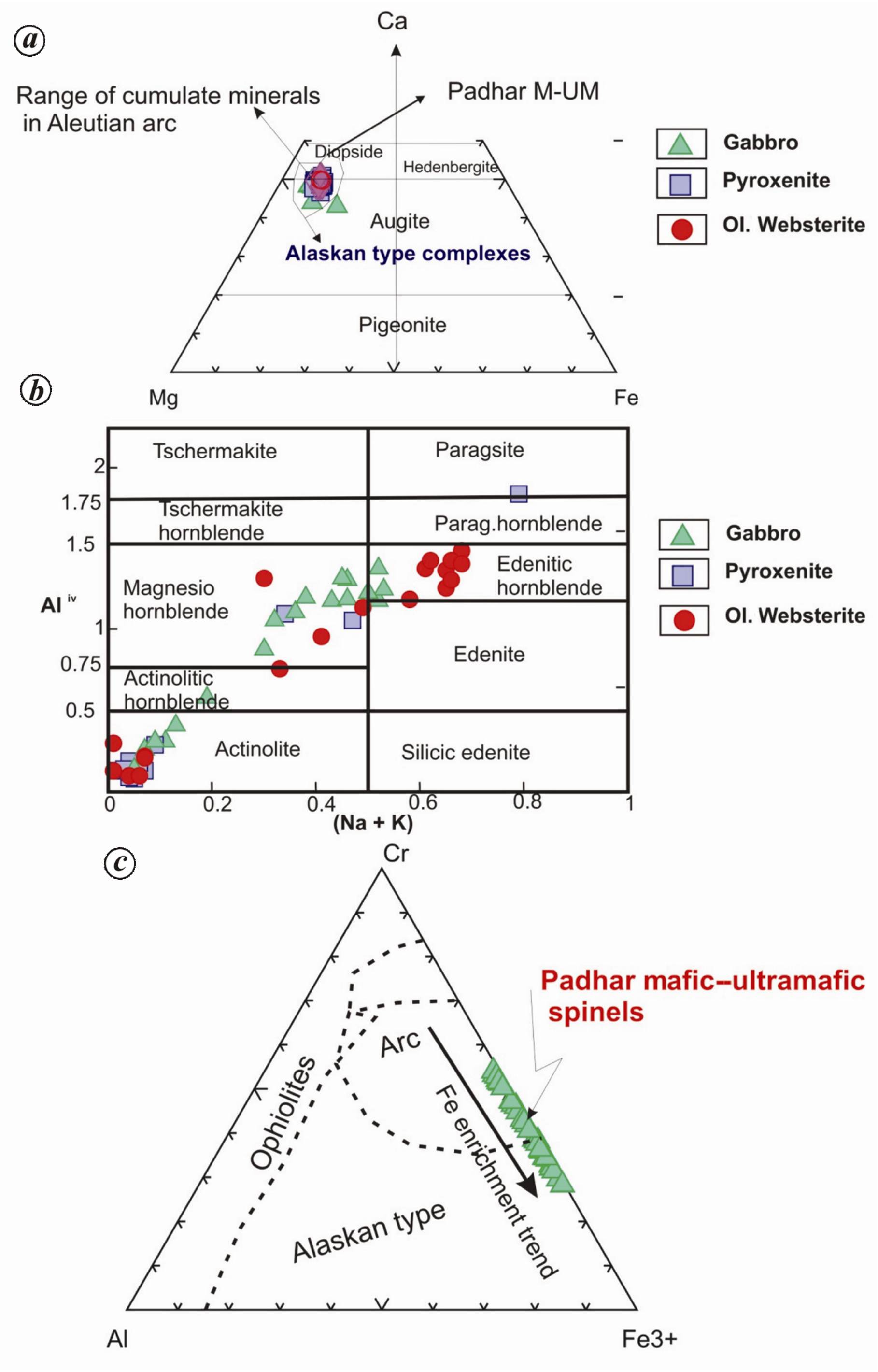

Figure 3. ***a***, Composition of clinopyroxene from Padhar M–UM fall into the field of clinopyroxene of ultramafic cumulate in the island arc of Aleutian, field after ref. 33 showing Alaskan signature. ***b***, Amphibole composition of Padhar M–UM complex (after Leake *et al.*[34]). ***c***, Al–Cr–Fe^{3+} trend of Cr-spinel of Padhar M–UM showing Alaskan-type trend and fields are adapted[35].

and 20 sec respectively, for silicates and sulphides for both peak and background determination. All the elements were determined using natural standards, except Cr, Ti and Al. For determination of Ni, Au, Co and Ag 100% metal standards were used. Table 1 summarizes the representative analytical data. REE were analysed by ICP-MS (ELAN-DRC model) at GSI, Nagpur. Analyses for Cu, Cr and Ni were done using AAS. Table 1 presents the analytical data.

Olivine grains were observed in the altered peridotite. They showed fosterite (Fo) ranging from 71% to 77% and low CaO content having similarity with olivine (Fo ranging

Table 2. Whole-rock major, trace, rare earth data of Padhar mafic–ultramafic suites, Betul Belt, MP

Sample no.	RM-50	RM-52	RM-67	RM-68	RM-73	RM-74
Rock type	Ser. clinopy	Ser. wehrlite	Ol. websterite	Pyroxenite	Hbl-Gabbro	Ol. websterite
Coordinates	N 22°06′03″ E 77°51′00″	22°05′57″ 77°50′57″	22°02′13″ 77°47′28″	22°02′25″ 77°47′38″	22°06′14″ 77°46′43″	22°05′46″ 77°48′05″
SiO_2	39.73	42.06	47.85	50.57	46.77	49.79
TiO_2	0.18	0.3	0.23	0.25	0.83	0.33
Al_2O_3	5.05	7.47	3.91	5.55	14.42	3.6
Fe_2O_3	11.04	10.63	10.38	10.51	10.91	11.86
MnO	0.16	0.14	0.18	0.17	0.18	0.22
MgO	27.37	26.66	24.87	22.48	6.85	19.99
CaO	6.57	3.82	4.86	6.5	10.72	9.26
Na_2O	0.05	0.24	0.2	0.13	1.93	0.26
K_2O	0.05	0.15	0.13	0.05	0.44	0.27
P_2O_5	0.03	0.04	0.04	0.02	0.07	0.02
LOI	10.47	6.02	2.52	4.6	2.88	1.16
Total	100.7	97.53	95.17	100.83	96	96.76
Cr	0.43%	0.13%	0.23%	0.10%	350 ppm	0.19%
Ni	700	800	600	600	80	490
Co	90	85	75	70	35	60
Cu	25	25	160	170	45	25
Pb	15	20	10	20	20	20
Zn	10	20	15	10	15	10
Sc	11.28	8.46	13.82	15.12	12.35	14.61
Y	12.43	10.27	6.66	10.9	29.88	18.92
Nb	4.97	4.03	3.26	4.01	5.99	5.81
Hf	7.13	5.42	3.65	1.1	5.7	2.27
Ta	1.82	0.35	0.73	3.96	1.14	4.76
Th	8.32	4.24	4.46	12.24	2.93	36.59
U	0.94	0.47	0.22	0.65	0.61	0.74
La	13.97	8.69	4.61	5.28	11.44	15.59
Ce	34.62	24.73	17.33	58.36	27.19	326.42
Pr	4.03	2.76	1.86	2.61	3.51	6.46
Nd	15.97	10.79	7.74	11.12	14.03	27.01
Sm	0.78	0.62	0.38	0.49	1.02	0.83
Eu	3.36	2.15	1.63	2.59	3.47	5.93
Gd	0.46	0.34	0.23	0.41	0.77	0.84
Tb	2.95	2.03	1.5	2.32	3.86	5.15
Dy	2.68	2.05	1.35	2.48	5.44	4.78
Ho	0.49	0.39	0.28	0.45	1.15	0.89
Er	1.39	1.17	0.72	1.28	3.43	2.38
Tm	0.2	0.19	0.12	0.2	0.58	0.34
Yb	1.19	0.98	0.72	1.19	3.49	1.91
Lu	0.17	0.16	0.1	0.18	0.53	0.26

from 73 wt% to 82 wt%) from typical Alaskan-type settings such as the Klamath Mountains California[21]. Clinopyroxene (Cpx) from various intrusive rocks of PMUC was Ca-rich, ranging in composition from diopside to diopsidic augite. It contained low Al_2O_3 (0.77 wt%–2.24 wt%), TiO_2 (0.03 wt%–0.53 wt%) and Na_2O (0.11 wt%–0.47 wt%) akin to clinopyroxene of Alaskan-type rocks having characteristics of Ca-rich, low Al_2O_3 (<3.5 wt%), TiO_2 (<0.8 wt%) and Na_2O (<0.5 wt%)[5]. The amphiboles in the complex were Mg-rich, mainly pargasitic; edenitic and tschermakitic hornblendes were also seen (Figure 3 *b*). The observed compositional variations in amphibole were also similar to those in Alaskan-type ultramafic–mafic rocks from the Bear Mountain[21], Blashke Islands–Kane Peak–Klukwan[2], and Abu Hamamid intrusive complexes[22]. Both Cr-spinel and Cr-magnetite were present and showed a clear differentiation trend from an intermediate Cr–Al-rich spinel to Cr-magnetite (Figure 3 *c*). Similar Fe^{3+} increasing trend in spinels has been reported from Alaskan-type complexes[6], but not from ophiolites or layered intrusions[23].

Table 2 presents whole-rock major, trace and REE data. Primitive mantle normalized patterns showed enriched large ion lithophile elements (LILE), positive Pb anomaly and negative Nb, Sr, Zr and Hf anomalies with chondrite normalized flat HREE patterns. It indicates that the PMUC parental magma was generated from a subduction-related metasomatized, enriched mantle source and emplaced in an continental magmatic arc setting (Figure 4 *a*). Trace element ratio of La/Nb versus La/Yb showed subduction signature (Figure 4 *b*). These geochemical signatures are akin to Alaskan-type complex. The geochemical trends of all the rocks from PMVC coupled with complementary mineralogical evidences indicate melt derivation from a common source and evolution though fractionation, showing tholeiitic signature[14]. Presence of hornblende and phlogophite in the cumulate rock as intercumulous phases suggests the role of high-Al hydrous basaltic magmas in the formation of PMUC, while Alaskan-type rocks (cumulates) are known to be derived from crystallization of hydrous mafic and ultramafic magmas[2]. Such characters are typical products of subduction-associated arc magmas[24] or arc–root complexes[25,26].

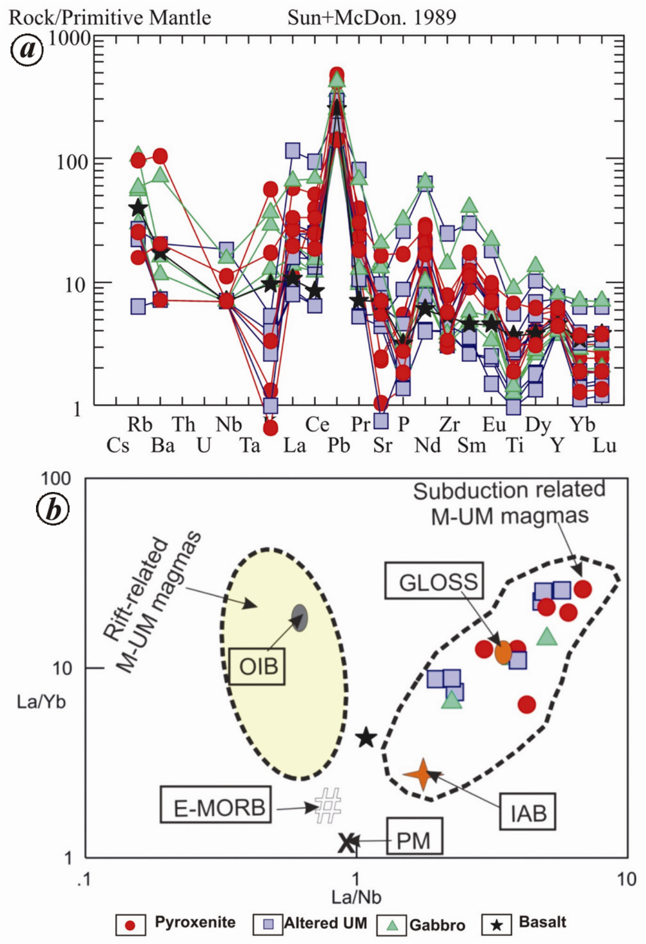

Figure 4. ***a***, Primitive mantle-normalized plot showing incompatible element abundances for the genesis of subduction-related mafic magmas from Padhar area[36]. ***b***, La/Nb versus La/Yb variation in the Padhar mafic magmas. Compositions of PM (primitive mantle), EMORB, OIB, IAB (Island Arc Basalt) and GLOSS are shown for comparison[37]. GLOSS and IAB explain the chemistry of subduction-related magmas of the Padhar area.

Presence of concentric zoning in the field, clinopyroxene and hornblende-rich lithologies and paucity of Opx or plagioclase distinguish PMUC from Alpine-type suite of rocks, ophiolites of orogenic belts as well as from the stratiform layered intrusive in stable cratonic settings[21,22,27]. Apart from petrological similarities, the relationship between PMUC and Alaskan-type complexes is further supported by the following evidences: (1) Fe^{3+}, Ti-rich spinels (Figure 3 *c*); (2) calcic-rich and Al_2O_3 and TiO_2-poor Cpx (Figure 3 *a*); (3) very low CaO content in olivine, and (4) rare graded layers evidencing crystal accumulation. These geological features characteristic of PMUC are significantly similar to Alaskan-type complexes, generally found in Alaska and elsewhere.

The Alaskan-type complexes are characterized by the usual presence of PGE with Pt–Fe alloy-rich mineral assemblage[28]. Recently, platinum mineralization has been reported from Temra and Sarni gabbro-anorthosites in the Betul Belt[8]. Very few Alaskan-type complexes are known to have magmatic Cu–Ni–PGE deposits[29]. However, geological setting of these deposits suggests that Alaskan-type complexes and continental subduction zones need to be explored in detail for magmatic Cu–Ni–PGE mineralization[30,31]. The field, petrological and geochemical studies suggest that PMUC is an Alaskan-type intrusion from Central India. This opens a new window for the study of tectonics and geodynamics of CITZ and PMUC as a favourable target for detailed PGM exploration in the Betul Belt.

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