Ortho- and clino-pyroxenes from the charnockite series of Amaravathi, Andhra Pradesh, South India

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SUMMARY. The chemical analyses, structural formulae, and optical data of seven orthopyroxenes and six clinopyroxenes, all from the charnockite series of Amaravathi, are presented. The ortho-pyroxenes are in the hypersthene-ferrohypersthene range while the clinopyroxenes are in the sahlite range. The aluminous nature of the pyroxene is believed to be the result of high pressure. The clino-pyroxenes have the granulite trend on the Wo–En–Fs plot. The tie-line projections and the K_D values for the pyroxene pairs indicate conditions of chemical equilibrium around 670 °C for the charnockite series of Amaravathi.

DURING the course of geological mapping of about 250 sq. km area around Amara-vathi (16° 20′ to 16° 35′ N., 80° 21′ to 80° 28′ E.), paragneisses, a charnockite series consisting of pyroxene granulites (basic) and charnockites (acidic), granites, and dolerites are noticed. The interbanded paragneisses and pyroxene granulites of the basement rocks were successively emplaced by charnockites, granites, and dolerites. This paper is a concise account of ortho- and clino-pyroxenes from the charnockite series.

Orthopyroxenes. Seven orthopyroxenes were chemically analysed and proved to be hypersthene or ferrohypersthene. The chemical and optical data and the atomic ratios of both ortho- and clino-pyroxenes are given in table I.

The pleochroism of the orthopyroxene is α pink, β yellow, γ green, the intensity varying from section to section, from grain to grain within the section, and from portion to portion within the grain.

The range of composition of the major oxides of the pyroxenes of Amaravathi is well within that of the pyroxenes of Kondapalli and Madras (Leelanandam, 1967), excepting that TiO_2 is less in pyroxenes of the present area. CaO is generally low in the orthopyroxenes and related to exsolution clinopyroxene lamellae.

The lower limit of Al_2O_3 in orthopyroxenes from Amaravathi is 2·56 % whereas the upper limit of Al_2O_3 in orthopyroxenes of igneous rocks is about 2 % (Muir, 1951). High Al_2O_3 in pyroxenes is attributed to the host-rock chemistry by Howie (1965) and Leelanandam (1967), to host-rock chemistry and to the nature of the coexisting phases (more aluminous pyroxenes coexist with more sodic plagioclase) by Binns (1965), to their formation from aluminium-bearing minerals like hornblende, biotite, and garnet by Murty (1965), and to high pressures by Eskola. Those parent rocks that have

TABLE I. *Chemical analyses and optical data of ortho- and clino-pyroxenes.*
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Constituents	1		2		3		4		5		6		7
	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py
SiO_2	49·16	50·18	49·55	49·15	49·79	50·58	50·70	48·06	50·04	50·60	49·40	50·30	50·04
Al_2O_3	4·10	3·61	2·56	4·03	3·19	2·52	3·52	5·89	4·82	3·49	3·92	3·83	2·81
TiO_2	0·11	0·13	0·30	0·41	0·16	0·30	0·18	0·36	0·19	0·27	0·28	0·30	0·12
Fe_2O_3	0·76	2·20	1·04	0·91	0·80	1·12	1·31	2·22	1·74	1·66	1·26	1·71	1·29
FeO	29·92	11·54	29·76	12·04	29·34	12·04	26·08	10·22	21·08	7·87	31·82	14·54	29·40
MnO	0·76	0·19	0·74	0·38	0·66	0·29	0·59	0·13	0·48	0·16	0·76	0·24	0·63
MgO	14·73	10·96	15·41	11·08	14·84	11·52	16·64	11·71	21·32	14·01	11·57	9·76	14·51
CaO	0·48	20·21	0·43	20·26	1·16	21·04	0·86	21·00	0·18	21·29	0·74	18·40	0·98
Na_2O	0·09	0·86	0·19	0·66	0·16	0·68	0·06	0·06	0·53	0·16	0·59	0·79	0·21
K_2O	0·07	0·11	0·09	0·14	0·06	0·07	0·16	0·17	0·06	0·14	0·08	0·13	0·11
H_2O	0·03	—	0·04	0·05	0·08	—	0·06	0·08	0·05	0·04	—	0·02	0·02
Sum	100·21	99·99	100·11	100·11	100·24	100·16	100·16	100·37	100·12	100·12	100·21	100·02	100·12

Number of metal atoms on the basis of 6 oxygens:

	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py
Si	1·904	1·904	1·927	1·873	1·925	1·919	1·929	1·817	1·861	1·886	1·936	1·922	1·945
Al^{iv}	0·096	0·096	0·073	0·127	0·075	0·081	0·071	0·183	0·139	0·114	0·064	0·078	0·055
Al^{vi}	0·090	0·063	0·044	0·051	0·069	0·033	0·084	0·080	0·071	0·039	0·115	0·091	0·071
Ti	0·002	0·002	0·009	0·011	0·007	0·009	0·007	0·011	0·011	0·009	0·009	0·009	0·002
Fe^{3+}	0·023	0·064	0·028	0·055	0·023	0·032	0·037	0·063	0·049	0·049	0·038	0·050	0·037
Fe^{2+}	0·965	0·364	0·966	0·382	0·944	0·380	0·829	0·315	0·654	0·246	1·040	0·460	0·952
Mn	0·026	0·007	0·023	0·014	0·023	0·009	0·018	0·002	0·016	0·007	0·026	0·007	0·019
Mg	0·856	0·624	0·898	0·633	0·861	0·655	0·950	0·664	1·190	0·783	0·680	0·558	0·840
Ca	0·021	0·820	0·016	0·827	0·049	0·853	0·037	0·850	0·009	0·850	0·031	0·753	0·042
Na	0·009	0·068	0·014	0·050	0·014	0·050	0·009	0·036	0·013	0·045	0·014	0·059	0·014
K	0·005	0·005	0·005	0·005	0·005	0·005	0·009	0·009	0·004	0·004	0·005	0·005	0·005
WXY	2·009	2·017	2·003	2·028	1·995	2·026	1·980	2·030	2·013	2·032	1·958	1·992	1·982
Wo	1·14	45·34	0·87	44·91	2·63	45·17	2·01	46·29	0·48	45·24	1·75	42·51	2·28
En	46·46	34·51	47·77	34·38	46·44	34·69	52·32	36·17	64·21	41·67	38·55	31·53	46·01
Fs	52·40	20·15	51·37	20·72	50·94	20·12	45·65	17·53	35·30	13·09	59·40	25·97	51·71

Optical data°

	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py	C.Py	O.Py
γ:[001]	—	43°	—	42°	—	43°	—	42°	—	44°	—	44°	—
$2V_\alpha$	53°	—	55°	—	54°	—	55°	—	61°	—	57°	—	56°
$2V_\gamma$	—	51°	—	52°	—	51°	—	52°	—	59°	—	49°	—
β	1·722	—	1·724	—	1·720	—	1·719	—	1·706	—	1·735	—	1·723
γ−α	0·016	0·023	0·015	0·022	0·015	0·023	0·016	0·024	0·013	0·025	0·018	0·024	0·016

Ortho- and Clino-pyroxenes from: 1 to 5, Pyroxene granulite; 6, Intermediate charnockite; 7, Ortho-pyroxene from charnockite.

Al_2O_3 contents of 12·70 %, 13·23 %, and 15·43 % contain pyroxenes with 4·82 %, 2·56 %, and 3·52 % of Al_2O_3 respectively. The rock with sodic plagioclase (An_{30}) contains pyroxene of 2·81 % Al_2O_3, whereas the rock with plagioclase (An_{50}) contains pyroxene of 4·82 % Al_2O_3. The pyroxenes of the present area are not derived from the aluminium-bearing minerals. Under these circumstances, it appears probable that the aluminous pyroxenes are as a result of high pressures (Eskola, 1957). The experimental work of Boyd and England (1960) lends support to this inference.

The Clinopyroxenes prove to be sahlites (table I). The clinopyroxenes coexisting with orthopyroxenes exhibit a significant difference between the trends of the metamorphic and igneous clinopyroxenes on a Wo–En–Fs plot indicating restriction of the

immiscibility field between lime-rich and lime-poor pyroxenes at the higher temperatures of igneous rocks (Binns, 1962, 1965). Binns suggests that the calcium contents of mutually coexisting pyroxenes might prove useful in indicating crystallization trends. The present clinopyroxenes (fig. 1) lie along the granulite trend, positioned in
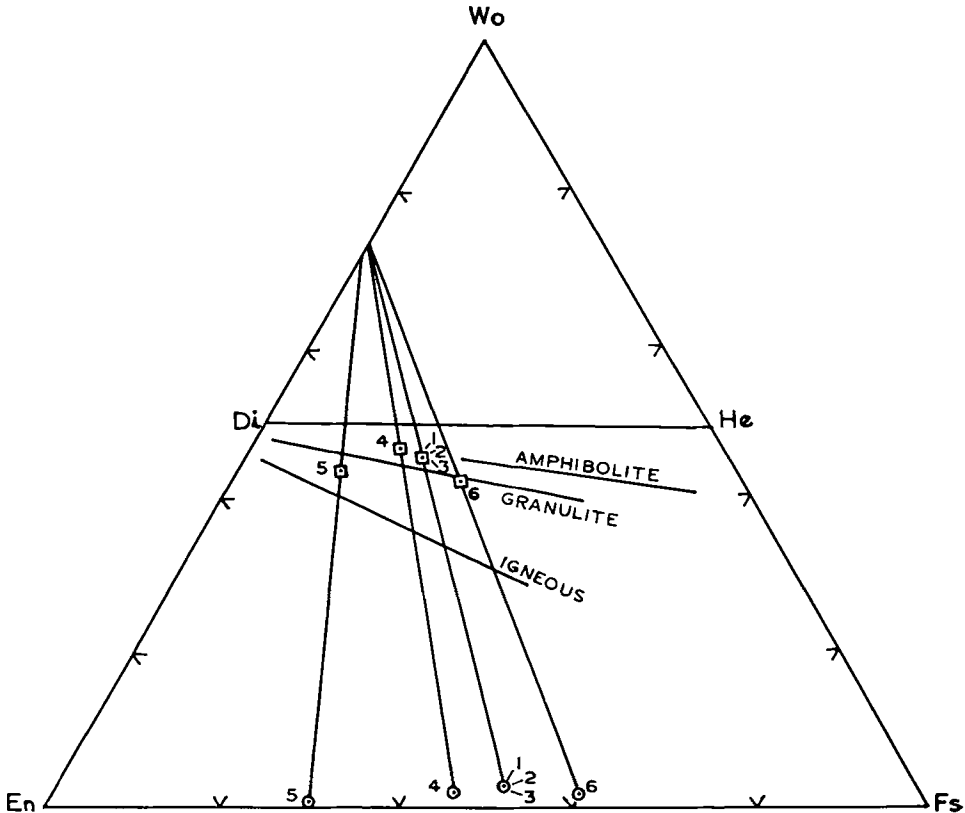

FIG. 1. Wo–En–Fs diagram showing tie-lines of coexisting pyroxenes. Trend lines from Binns (1965).

between the amphibolite and igneous trends. That the trend line slopes more in the iron-rich portions than in the magnesian is explained by the Fe^{2+} more readily replacing Ca^{2+} in the octahedrally coordinated site than does magnesium, the ionic radius of Fe^{2+} being nearer that of Ca^{2+}.

Coexisting pyroxenes. The chemical analyses of the coexisting pyroxenes were further examined to check the attainment or otherwise of chemical equilibrium and to gauge the temperature of equilibrium.

The literature on the pyroxene pairs shows that the positioning of the tie-lines around Wo_{75} (fig. 1) is the same for all pyroxenes, igneous or metamorphic, crystallized under equilibrium conditions. The tie-line study helps to show whether or not the

pyroxenes crystallized under conditions of equilibrium, but does not help in distinguishing the igneous assemblages from metamorphic ones.

Mueller (1960, 1961), Kretz (1961, 1963), and Bartholomé (1961, 1962), show that the distribution coefficient of magnesium and iron (K_D) in coexisting pyroxenes is useful in distinguishing igneous pyroxenes from metamorphic ones. Kretz (1961) concludes that K_D is a function of temperature and pressure and is independent of chemical variation, although Binns (1962) disputes the latter point from his study of the Broken Hill pyroxenes. Kretz (1963) observed that K_D values close to 0·54 are for pyroxene pairs from rocks believed to be metamorphic and those around 0·73 are for pyroxene pairs from igneous rocks.

The K_D values for the six pyroxene pairs vary from 0·53 to 0·57 with an average of 0·55. The temperature of about 670 °C obtained (Kretz, 1963) for pyroxene pairs from charnockites of Madras having an average K_D value of 0·54 holds good for the pyroxene pairs from pyroxene granulites of Amaravathi.

Atkins (1969), Hietanen (1971), and Wilson and Middleton (1968) obtained respectively K_D values of 0·67 for Bushveld intrusion, 0·61 for pyroxene diorite from Bucks Lane Pluton, and 0·56 for Fraser Range metagabbro. Hietanen remarks that K_D for the igneous rocks ranges from 0·74 to at least 0·61, and to 0·54 if the charnockites studied were igneous. It is thus evident that the K_D values help know temperatures of later recrystallization but not temperatures of earlier crystallization from melts. The K_D values may be viewed more as an indicator of the physico-chemical conditions of pyroxene formation than strictly as a distinction between igneous and metamorphic assemblages.

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