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Applicability of garnet-cordierite (Gt-Crd) geothermometer

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ABSTRACT

The garnet-cordierite pairs are commonly found in the assemblages of granulites and hence are suitable for estimating equilibrium temperature of these metamorphic rocks. At present, there are many calibrations of garnet-cordierite (Gt-Crd) thermometer that may confuse geologists in choosing a reliable thermometer. To test the accuracy of the garnet- cordierite thermometers, we have applied eleven models formulated by a number of researchers since (1976) till date. We have collected 70 samples from the literature all over the world, which has been processed through "Gt-Crd.EXE" software. Based on the present study, we have identified a set of the best among all the eleven models which were considered under this comparative study. We have concluded that the five garnet-cordierite thermometers are the most valid and reliable of this kind of thermometer (Holdaway and Lee, 1977; Perchuk et al.,1985; Thompson, 1976; Wells, 1979 and Aranovich and Podlesskii, 1989).

Keywords: Garnet; Cordierite; Exchange reaction; Granulite; Comparative study

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INTRODUCTION

To decipher the metamorphic conditions and for understanding the crustal evolution, a valid geothermobarometry serves as a fundamental tool. In the last few decades, several geothermobarometers have been proposed for determining the metamorphic conditions of rocks ranging from greenschist to eclogites facies with a range of pressures.

The validity of a thermometer is a prerequisite in the study of metamorphism. Several thermobarometric studies had been undertaken in the past few years, which led to the development of a range of thermometers and barometers, such as garnet-biotite thermometer (Wu and Cheng, 2006; Thomas and Rana, 2019), garnet-clinopyroxene thermometer (Jahnson et al., 1983; Fu et al., 1998), garnet-orthopyroxene thermometer (Thomas et al., 2018).

The study of garnet-cordierite (Gt-Crd) geothermometry has a long history with several versions of geothermometers. However, these diverse calibrations may be confusing to petrologists in choosing a suitable version. With the development of geothermobarometric studies, it appears necessary to do a review for a given thermometer or barometer every decade or so. Now in this paper, authors summarize and compare the available garnet-cordierite thermometer in order to recommend the best calibrations to geologists/petrologists.

GARNET-CORDIERITE EXCHANGE THERMOMETERS

The most widespread occurrences of cordierite in the pelitic metamorphic rocks occur with various combinations of quartz, muscovite, potash feldspar, chlorite, biotite, aluminosilicate, staurolite and almandine (Turner and Hill, 1968). With increasing temperature, these may be broadly characterised as (1) Cordierite-Muscovite, (2) Cordierite-K-feldspar and (3) Cordierite-K-feldspar-Almandine assemblages. Much experimental work on cordierite has involved end member composition (Richardson, 1968; Seifert and Schreyer, 1970; Newton, 1972; Seifert, 1970). The Fe-Mg cordierite system has been experimentally investigated by Hensen and Green (1971, 1972 and 1973) and Currie (1971). Haase and Rutherford (1975) were the first to study Fe-Mg cordierite stability with muscovite and with K-feldspar. In last two decades, several workers have done experimental calibration for Fe-Mg cordierite system.

Quantification of the garnet cordierite Fe-Mg equilibrium is a widely applied thermometer for the assemblages of granulites. The distribution of the Fe^{2+} and Mg between coexisting garnet and cordierite is expressed by the exchange reaction using equations given by (Thompson, 1976; Holdaway and Lee, 1977; Wells, 1979; Perchuk et al.,1985; Bhattacharya et al.,1988; Aranovich and Podlesskii, 1989; Perchuk,1991; Nichols et al.,1992; Dwivedi et al.,1998 A & B and Kaneko and Miyano, 2004) are as follows:

$$\frac{1}{3}Fe_3Al_2Si_3O_{12}+\frac{1}{2}Mg_2Al_4Si_5O_{18}$$
$$=\frac{1}{3}Mg_3Al_2Si_3O_{12}+\frac{1}{2}Fe_2Al_4Si_5O_{18}$$

The partitioning of the Fe^{2+} and Mg, expressed by the distribution coefficient between coexisting garnet and cordierite have clearly shown that this distribution is a function of both physical conditions as well as compositional variations of the phases involved:

$$K_D=\frac{\left(\frac{Fe^{2+}}{Mg}\right)Gt}{\left(\frac{Fe^{2+}}{Mg}\right)Crd}$$

Exchange thermometers mainly imply the exchange of Fe and Mg between coexisting silicates, characterized by small ΔV compared to large ΔH so that equilibrium constant isopleths have rather steep slope. This Fe-Mg exchange equilibrium has been formulated by a number of workers by obtaining standard state thermodynamic data either by empirical method or by experiments involving the crystalline solutions (garnet and cordierite) between the two cations, Fe and Mg. A brief description of various models considered for this comparative study is summarized as follows:

Thompson (1976)

Thompson (1976) gave an empirical calibration for garnet-cordierite assemblage studying the detailed behaviour of mineral assemblages during progressive metamorphism of pelitic rocks for the KFMASH model system. The equation for calculation of temperature is:

$$T(k)=\frac{2725+0.0155(P-1)}{LnK_D+0.896}$$

If the garnet and cordierite are ideal solid - solutions, then Distribution coefficient KD is calculated as:

$$K_D=\frac{X_{Fe}^{Gt}*X_{Mg}^{Crd}}{X_{Mg}^{Gt}*X_{Fe}^{Crd}}$$

Where,

$$X_{Fe}^{Gt}=\frac{Fe}{Fe+Mg+Ca+Mn}$$

$$X_{Mg}^{Gt}=\frac{Mg}{Fe+Mg+Ca+Mn}$$

$$X_{Fe}^{Crd}=\frac{Fe}{Fe+Mg}$$

$$X_{Mg}^{Crd}=\frac{Mg}{Fe+Mg}$$

Holdaway and Lee (1977)

Holdaway and Lee (1977) gave an empirical calibration by determining the stability relations of Fe-Mg cordierite with K-feldspar for conditions of muscovite-quartz instability, applicable to high grade metamorphism of pelitic rocks as:

$$T(K)=\frac{3095+0.0152(P-1)}{LnK_D+1.354}$$

Wells (1979)

Wells (1979) tried to explain the formation of granulite facies rocks of Southern West Greenland using thermometers calibrated against the result of phase equilibrium experiments giving equation as:

$$T(K)=\frac{2789-0.0148(P-1)}{LnK_D+0.802}$$

Perchuk et al. (1985)

Perchuk et al., (1985) formulated an equation for calculation of temperature of metamorphism for Aldan granulites as:

$$T(K)=\frac{3087+0.018(P-1)}{LnK_D+1.342}$$

Bhattacharya et al. (1988)

Bhattacharya et al., (1988) used naturally occurring garnet and cordierite extracting the interchange energy of Fe-Mg mixing in cordierite and the free energy change of the exchange equilibrium to formulate an equation for thermometer as:

$$T(K)=\frac{1814+0.0152(P-1)+1122(X_{Mg}-X_{Fe})Crd+1258(X_{Fe}-X_{Mg})Gt+1510(X_{Ca}+X_{Mn})Gt}{1.354+LnK_D}$$

Bhattacharya et al., (1988) have used Fe, Mg of cordierite and Fe, Mg, Ca and Mn of garnet as a factor in the equation. To check the relationship between composition and $\ln K_D$, authors have plotted the graphs as shown in (Figs.1a-f). The graph of LnK_D verses X_{Fe}^{Crd} (Fig.1a) shows a gentle negative slope which means that as the values of LnK_D increases, X_{Fe}^{Crd} values decreases gently. X_{Mg}^{Crd} (Fig.1b) shows a horizontal slope with LnK_D, which means an equilibrium relationship. X_{Fe}^{Gt} (Fig.1c) values increases as the LnK_D value increases showing a positive relationship with LnK_D. The graph of LnK_D vs X_{Mg}^{Gt} (Fig.1d) shows a negative slope as the values of LnK_D increases, X_{Mg}^{Gt} value decreases. X_{Mg}^{Gt} show higher values because magnesium content increases as the grade of metamorphism increases as shown in (Fig.1d). Although, X_{Ca}^{Gt} (Fig.1e) shows clustering at very lower range, it decreases gently as the value of LnK_D increases. As the sample data collected are of granulites facies rocks only, the content of Mn decreases as the grade of metamorphism increases as shown in (Fig.1f). It shows a gentle positive relation with LnK_D.

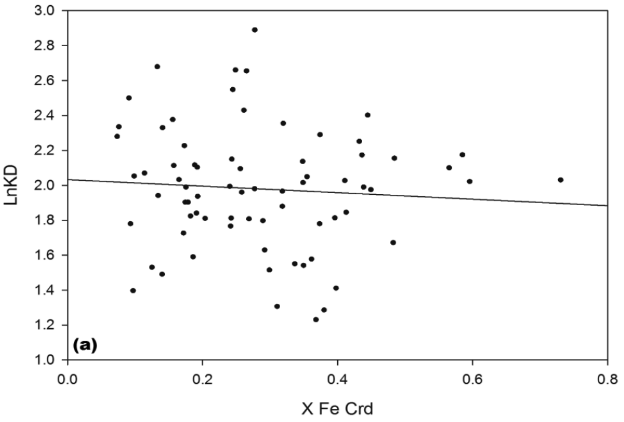

Fig. 1(a): LnK_D verses X_{Fe}^{Crd}.

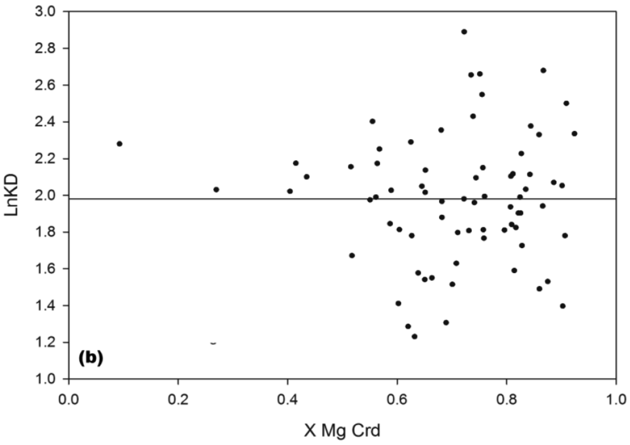

Fig. 1(b): LnK_D verses X_{Mg}^{Crd}.

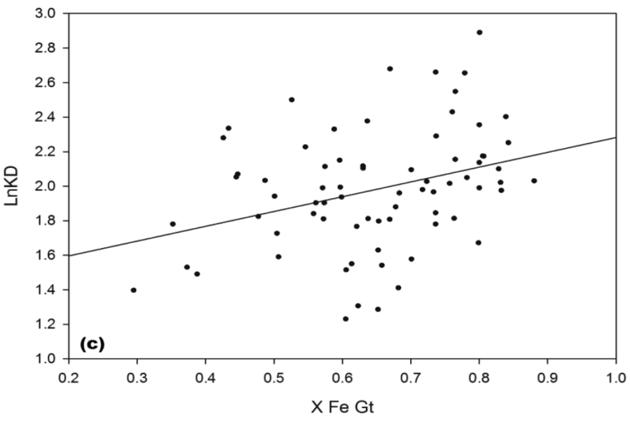

Fig. 1(c): LnK_D verses .

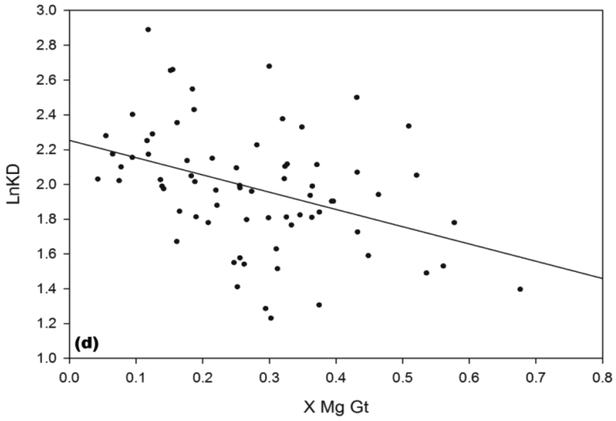

Fig. 1(d): LnK_D verses X_{Mg}^{Gt}.

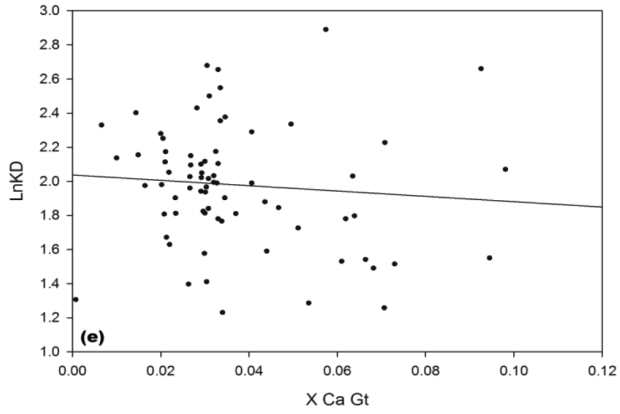

Fig. 1(e): LnK_D verses X_{Ca}^{Gt} .

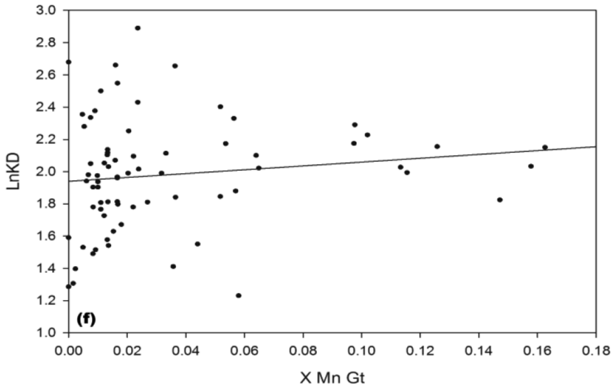

Fig. 1(f): LnK_D verses X_{Mn}^{Gt} .

Aranovich and Podlesskii (1989)

Aranovich and Podlesskii, (1989) used experimental data on equilibria involving rock forming minerals in high grade metapelites to derive an internally consistent system of mineralogical thermometers based on component reactions and excess mixing properties of solid solutions formulating an equation as:

$$T(K) = \frac{3087 + 0.0178(P-1) - A}{LnK_D + 1.343 + B}$$

Perchuk (1991)

Perchuk (1991) has attempted to construct internally consistent thermometer adopting nearly ideal solid solution models for garnet-cordierite pair as

$$T(K) = \frac{3020 + 0.0176(P-1) + 1074 * X_{Ca}^{Gt}}{LnK_D + 1.287}$$

Nichols et al. (1992)

Nichols et al., (1992) used experimental data based on non- ideal mixing on internally consistent gahnite-spinel-cordierite-garnet equilibria in FMASHZ system to formulate an equation for garnet-cordierite pair.

$$T(K) = \frac{2268 + 0.012632(P-1) - C - A}{LnK_D + 0.62889 + B}$$

Dwivedi et al. (1998)

Dwivedi et al., (1988) constructed a garnet-cordierite thermometer estimating Fe-Mg non-ideality in cordierite through a multiple linear regression method. Their calibration was based upon Holdaway et al., (1997) ternary margules parameters and on Berman (1990) quaternary parameters for garnets.

$$T1(K) = \frac{[27018 + 0.13(P-1) - 2024(X_{Fe} - X_{Mg})Crd - A]}{[RLnK_D + 12.8 + B]}$$

$$T2(K) = \frac{[26932 + 0.13(P-1) - 887(X_{Fe} - X_{Mg})Crd - C]}{[RLnK_D + 12.36 + D]}$$

Kaneko and Miyano (2004)

Kaneko and Miyano (2004) calibrated garnet-cordierite thermometer using the results of Fe2+-Mg cation exchange experiments and utilising recently evaluated non-ideal mixing properties of garnet in terms of iterative multiple least square regressions of the experimental results.

$$T(K) = \frac{[-26144 + (-0.122 + W_V^{Gt}) * (P-1) + W_H^{Gt} - 80.449 * (X_{Fe} - X_{Mg})Crd]}{[-12.7094 - RLnK_D + W_S^{Gt} + 1.642(X_{Fe} - X_{Mg})Crd]}$$

VALID GCRD GEOTHERMOMETRY IN GRANULITES

Granulites are typical rocks of the earth's middle to lower crust under high temperature conditions. They are found as xenoliths in basaltic volcanic rocks, mainly within continental rifts, but most granulites occur as complexes or terranes in orogenic settings. Orogenic granulites display a wide compositional range (Harley, 1989) and are known from a variety of collisional belts that formed during different episodes since the Archaean. Determination of bulk rock and mineral compositions, calculation of peak equilibration conditions, and dating of orogenic granulites that provide us with important constraints on the thermal and chemical structure of the earth continental crust at different geological times. Harley (1989) showed that equilibration conditions deduced from the natural orogenic granulites cover a wide range. In particular, pressures are highly variable, and the granulite field may be divided into a low pressure, a medium pressure and a high pressure facies according to Green and Ringwood (1967). Peak temperatures for many granulites terrain scatter around 800°C (Bohlen, 1987), but an increasing number of ultra-high temperature granulites complexes (900-1100°C and 0.7-1.3 GPa) are being recognized (Dasgupta and Sengupta, 1995; Klemd and Brocker, 1999; Hokada, 2001).

To test the validity and applicability of garent-cordierite (Gt-Crd) thermometry, we have collected 70 samples (60 of granulites and 10 of UHT/UHP) from the literature all over the world. Selection of samples fit the following criteria (Wu and Cheng, 2006; Thomas et al., 2018; Thomas and Rana, 2019):

1. There is a clear description of textural equilibrium among garnet and cordierite in the literature.
2. There is detailed and high quality electron microprobe analyses of the minerals involved, at least SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O and K_2O, and there stoichiometry of the analysed minerals was confirmed.
3. Core composition of garnet and rim composition of cordierite has been mostly used. If there is growth zoning in garnet, only the rim composition was used, and accordingly, only the rim composition of matrix cordierite has been used.
4. Data is used where elemental oxide totals for the minerals analyses were 100 ±1.5 percent.

The 70 samples (60 of granulites and 10 of UHT/UHP) listed in the Table-1 falls in the mineral composition ranges: X_{Fe}= 0.0735-0.5958 (mostly between 0.20-0.50), X_{Mg}= 0.0925-0.9238 (mostly between 0.55-0.9) in cordierite; X_{Fe}= 0.2948-0.8802 (mostly between 0.5-0.80), X_{Mg} = 0.0426-0.6764 (mostly between 0.10-0.40), X_{Mn}= 0.0-0.1626 (mostly between 0.01-0.04) and X_{Ca}= 0.00076-0.0981 (mostly between 0.01-0.05) in garnet.

Table 1: Data of X_{Fe}^{Crd} and X_{Mg}^{Crd}, X_{Fe}^{Gt}, X_{Mg}^{Gt}, X_{Ca}^{Gt}, X_{Mn}^{Gt}, X_{Fe}^{Crd} , K_D, and $\ln K_D$ of different rocks samples by different authors.

Data of different authors	X_{Fe}^{Crd}	X_{Mg}^{Crd}	X_{Fe}^{Gt}	X_{Mg}^{Gt}	X_{Mn}^{Gt}	X_{Ca}^{Gt}	K_D	$\ln K_D$
Begin and Pattison, 1994	0.2688	0.7311	0.6692	0.2987	0.011	0.0208	6.0921	1.807
Bingen et al., 1988	0.1744	0.8255	0.561	0.396	0.00833	0.0345	6.7052	1.9029
Blumel and Schreyer, 1977	0.4843	0.5156	0.7649	0.0943	0.1258	0.0149	8.6282	2.155
Boger and White, 2003	0.1921	0.8078	0.6303	0.3234	0.0132	0.033	8.1957	2.1036
Brown and Earle, 1983	0.3495	0.6504	0.6577	0.2621	0.0136	0.0664	4.6687	1.5409
Boullier and Barbey, 1988	0.3194	0.6805	0.8001	0.1615	0.0047	0.0335	10.54	2.355
Bucher-Nurminen and Ohta, 1993	0.4322	0.5677	0.8424	0.1164	0.0205	0.0205	9.5	2.2515
Clarke and Powell, 1991	0.3546	0.6453	0.782	0.1828	0.0075	0.0293	7.765	2.0496
Clarke et al., 1990	0.3959	0.604	0.7633	0.19	0.0166	0.03	6.1293	1.8131
Clarke et al., 2007	0.2919	0.708	0.6522	0.3103	0.0153	0.022	5.097	1.6286
Dempster et al, 1991	0.4448	0.5551	0.8389	0.0947	0.0518	0.0144	11.046	2.4021
Ding and Zhong, 1999	0.3365	0.6634	0.6135	0.247	0.044	0.0945	4.89	1.55
Dirks et al., 1991	0.4494	0.5505	0.8322	0.1414	0.0098	0.01644	7.2	1.9749
Droop, 1989	0.0932	0.9067	0.3521	0.5775	0.00837	0.0619	5.92	1.78
Droop et al., 2003	0.4129	0.587	0.73622	0.1652	0.05175	0.0467	6.33	1.845
Ellis and Hiroi, 1997	0.2402	0.7597	0.5968	0.2555	0.1155	0.032	7.385	1.994
Graessner and Schenk, 2001	0.4825	0.5174	0.799	0.1611	0.018	0.0213	5.317	1.6709
Greenfield et al., 2004	0.3482	0.6517	0.8	0.1766	0.0133	0.01	8.474	2.137
Grew, 1981	0.3182	0.6817	0.7332	0.2198	0.0166	0.03033	7.145	1.9665
Gross et al., 2009	0.3613	0.6386	0.7009	0.2558	0.0132	0.0299	4.84	1.577
Guevara et al., 2017	0.2448	0.7551	0.7651	0.1845	0.0167	0.0335	12.78	2.548
Mouri et al., 1996	0.3181	0.6818	0.6778	0.2214	0.057	0.0436	6.55	1.88
Halpin et al., 2007	0.2038	0.7961	0.5723	0.3636	0.0269	0.037	6.14	1.81
Harley, 1985	0.1858	0.8141	0.5065	0.4486	0	0.044	4.94	1.59
Harris et al., 1982	0.2424	0.7575	0.6375	0.3255	0.0134	0.0234	6.1211	1.8117
Hiroi et al., 1994	0.0987	0.9012	0.4448	0.521	0.0122	0.02186	7.79	2.053
Ishii et al., 2006	0.1574	0.8425	0.5744	0.3713	0.0332	0.021	8.2759	2.1133
Janák, 1999	0.4108	0.5891	0.7233	0.1366	0.1133	0.0266	7.59	2.0269
Joshi et al.,1993	0.1329	0.867	0.6696	0.2997	0	0.0305	14.57	2.679
Kotkova et al., 2007	0.2415	0.7584	0.6209	0.333	0.011	0.0338	5.84	1.766
Kienast and Ouzegane,1987	0.0909	0.909	0.5258	0.4313	0.011	0.031	12.18	2.5
Kumar and Chacko, 1994	0.2559	0.744	0.7005	0.2505	0.02211	0.0268	8.128	2.0953
Kundsen, 1996	0.7304	0.2695	0.8802	0.0426	0.0136	0.0635	7.616	2.0303
Likhanov et al., 2016	0.1909	0.809	0.5577	0.3749	0.03649	0.0308	6.3	1.84
Liu and Zhong, 1997	0.38	0.62	0.6521	0.2943	0	0.0535	3.6154	1.2852
Mahan et al., 2006	0.265	0.735	0.7788	0.1518	0.0363	0.033	14.23	2.6553

Table 1 Continued

Data of different authors	X_{Fe}^{Crd}	X_{Mg}^{Crd}	X_{Fe}^{Gt}	X_{Mg}^{Gt}	X_{Mn}^{Gt}	X_{Ca}^{Gt}	K_D	lnK_D
Martignole and Martelat, 2003	0.1651	0.8348	0.4868	0.3223	0.1578	0.032	7.6349	2.0327
Moraes et al,2002	0.1718	0.8281	0.5042	0.4324	0.0121	0.0511	5.6181	1.726
Mouri et al.,1996	0.1407	0.8592	0.588	0.3488	0.0564	0.0066	10.29	2.33
Norman and Clarke, 1990	0.1558	0.8441	0.6364	0.3197	0.009	0.0346	10.78	2.377
Okay, 1996	0.4362	0.5637	0.8065	0.1185	0.0536	0.0211	8.7911	2.1737
Okay et al., 2014	0.585	0.415	0.8051	0.0649	0.0974	0.03246	8.7966	2.1744
Osanai et al.,1998	0.173	0.8269	0.5458	0.2812	0.102	0.0708	9.275	2.227
Otamendi, 1999	0.258	0.7411	0.6833	0.2733	0.0166	0.0266	7.15	1.96
Perchuk et al., 1989	0.2612	0.7387	0.7606	0.187	0.0236	0.0282	11.47	2.43
Phillips and Nooy, 1988	0.5958	0.4041	0.8311	0.0746	0.0649	0.0292	7.54	2.0215
Pitra and De Waal, 2001	0.5654	0.4345	0.8284	0.0776	0.064	0.0291	8.19	2.1
Pownall, 2015	0.368	0.6318	0.6048	0.3024	0.058	0.034	3.43	1.23
Raith et al., 1997	0.125	0.875	0.3729	0.561	0.0049	0.061	4.65	1.53
Rao et al., 2011	0.0761	0.9238	0.4336	0.5092	0.0075	0.0495	10.329	2.335
Riciputi et al., 1990	0.1755	0.8244	0.571	0.3644	0.0317	0.0327	7.36	1.99
Rickers et al., 2001	0.1401	0.8598	0.3876	0.5357	0.0083	0.0682	4.43	1.49
Riesco et al.,2004	0.4387	0.5612	0.8	0.1389	0.0203	0.0406	7.36	1.99
Rollinson, 1982	0.374	0.625	0.737	0.1245	0.0977	0.0406	9.89	2.29
Santosh, 1987	0.1821	0.817	0.477	0.3459	0.1472	0.0296	6.1936	1.8235
Santosh et al., 2007	0.1341	0.8658	0.5008	0.4638	0.0061	0.0291	6.9672	1.9412
Scrimgeour et al., 2001	0.277	0.722	0.7171	0.2558	0.0067	0.0202	7.3	1.98
Scrimgeour et al., 2005	0.0735	0.09265	0.4258	0.05488	0.0053	0.02	9.77	2.28
Shimura et al., 2002	0.3977	0.6022	0.6819	0.2519	0.0357	0.0304	4.0988	1.4107
St-Onge et al., 2013	0.1928	0.8071	0.5986	0.3612	0.01	0.0301	6.9349	1.9366
Thomas, 2005	0.2488	0.7511	0.7362	0.155	0.016	0.09255	14.32	2.66
Tong and Wilson, 2006	0.097	0.9025	0.2948	0.6764	0.00233	0.0263	4.0393	1.3961
Tsunogae et al., 2008	0.114	0.886	0.447	0.432	0.0159	0.0981	7.93	2.07
Wang et al., 2009	0.2433	0.7567	0.5959	0.2144	0.1626	0.0268	8.644	2.15
Waters and Whales, 1984	0.3733	0.6266	0.7362	0.2083	0.022	0.033	5.9299	1.78
Whitney, 1992	0.2893	0.7106	0.6531	0.2659	0.0168	0.0639	6.0315	1.797
Yin et al., 2014	0.299	0.70098	0.60548	0.3121	0.0092	0.073	4.5498	1.5144
Yin et al., 2015	0.3105	0.6894	0.6229	0.3747	0.00155	0.00076	3.6909	1.3059
Zeh and Holness, 2003	0.2774	0.7225	0.8006	0.1182	0.0236	0.0574	12.63	2.89
Zeh et al., 2004	0.1785	0.8214	0.5733	0.3933	0.01	0.0233	6.7051	1.9029

RESULTS AND DISCUSSION

For the validation of the software (Thomas, 1994; Thomas, 1998; cited by Thomas, 1995, 2005; Joshi et al., 1993) a comparative study of different models, 70 pairs of data (60 of granulites and 10 of UHT/UHP) have been processed through this software and results are shown in Tables - 1 & 2 in a fixed format with X_{Fe}, X_{Mg} of cordierite and X_{Fe}, X_{Mg}, X_{Mn} & X_{Ca} for garnet along with temperature based on different workers.

Table 2: Data of the Calculated Temperature (ºC) of different rocks samples by different authors.

Data of different authors	Thomp son, 1976	Holdaway and Lee, 1977	Wells, 1979	Perchuk et al., 1985	Bhatt acharya et al., 1988	Aranovich and Podlesski, 1989	Perchuk, 1991	Nichols et al., 1992	Miyano et al., 2004	Dwivedi et al., 1998(a)	Dwivedi et al., 1998(b)
Begin and Pattison, 1994	769	735	762	741	763	748	744	710	1016	770	772
Bingen et al., 1988	734	705	725	711	719	718	718	672	719	740	748
Blumel and Schreyer, 1977	650	635	640	640	668	649	640	603	944	684	674
Boger and White, 2003	666	648	656	654	701	664	659	608	941	690	695
Brown and Earle, 1983	883	827	879	835	841	859	857	865	1122	878	890
Boullier and Barbey, 1988	593	586	582	591	664	609	595	554	891	654	643
Bucher-Nurminen and Ohta, 1993	622	611	611	616	652	628	616	583	911	676	659
Clarke and Powell, 1991	684	663	674	669	714	684	673	642	958	720	714
Clarke et al., 1990	767	733	759	739	758	755	745	729	1021	781	780
Clarke et al., 2007	843	795	838	802	803	809	807	786	1072	827	829
Dempster et al.,1991	581	575	570	580	620	589	578	538	882	642	619
Ding and Zhong, 1999	861	810	857	817	852	849	849	856	1138	884	902
Dirks et al., 1991	708	684	699	690	702	700	690	668	972	738	726
Droop, 1989	780	744	773	750	667	740	768	734	1046	797	794
Droop et al., 2003	755	723	747	729	759	753	741	725	1025	775	781
Ellis and Hiroi, 1997	700	677	691	683	764	693	688	643	991	721	724
Graessner and Schenk, 2001	825	780	819	787	767	800	791	790	1057	821	819
Greenfield et al., 2004	656	640	646	645	695	650	643	603	931	693	679
Grew, 1981	711	686	702	693	739	706	698	665	980	736	735
Gross et al., 2009	866	814	862	821	817	833	829	824	1092	851	854
Guevara et al., 2017	545	543	533	548	645	564	551	500	853	610	601
Mouri et al., 1996	742	712	733	718	772	736	728	701	1016	762	767
Halpin et al., 2007	766	732	758	739	757	746	747	709	1026	772	778
Harley, 1985	856	806	852	813	774	816	827	805	1095	847	852
Harris et al., 1982	768	733	760	740	759	747	744	703	1016	768	771
Hiroi et al., 1994	682	662	673	668	623	668	670	603	941	687	694
Ishii et al., 2006	663	646	653	651	685	656	653	592	934	676	683
Janák, 1999	691	669	681	675	727	689	679	646	979	718	715
Joshi et al., 1993	515	517	503	521	601	532	523	457	812	563	568
Kotkova et al., 2007	785	748	778	755	770	764	762	731	1034	786	791
Kienast and Ouzegane, 1987	557	553	544	558	579	563	561	488	841	584	596
Kumar and Chacko, 1994	669	651	659	656	717	667	659	615	946	698	697
Kundsen, 1996	690	668	680	674	563	719	690	688	963	729	739
Likhanov et al., 2016	756	724	749	731	748	736	737	694	1015	759	764
Liu and Zhong, 1997	1019	934	1021	943	898	959	964	1003	1209	973	982
Mahan et al., 2006	520	522	508	526	630	543	529	477	837	594	580
Martignole and Martelat, 2003	689	668	679	674	757	679	679	624	987	707	710
Moraes et al., 2002	802	761	795	768	754	773	782	752	1056	804	810

Table 2 Continued

Data of different authors	Thompson, 1976	Holdaway and Lee, 1977	Wells, 1979	Perchuk et al., 1985	Bhattacharya et al., 1988	Aranovich and Podlesski, 1989	Perchuk, 1991	Nichols et al., 1992	Miyano et al., 2004	Dwivedi et al., 1998 (a)	Dwivedi et al., 1998 (b)
Mouri et al., 1996	600	591	589	597	652	598	593	520	881	618	623
Norman and Clarke, 1990	588	581	576	586	649	596	590	530	877	625	631
Okay, 1996	645	630	634	636	672	648	638	603	933	689	677
Okay et al., 2014	645	630	634	635	614	655	640	613	937	684	680
Osanai et al., 1998	629	617	618	622	720	640	638	589	946	676	683
Otamendi, 1999	711	686	702	692	737	702	696	656	978	731	732
Perchuk et al., 1989	572	567	560	572	661	585	574	524	875	632	622
Phillips and Nooy, 1988	693	671	683	677	640	696	681	664	968	723	719
Pitra and De Waal, 2001	666	648	656	654	635	672	658	635	950	706	698
Pownall, 2015	1050	958	1053	967	930	976	782	1017	1232	986	991
Raith et al., 1997	885	829	881	836	744	825	857	844	1132	882	880
Rao et al., 2011	599	591	588	596	574	597	604	540	885	631	639
Riciputi et al., 1990	701	678	692	684	716	691	690	639	973	717	723
Rickers et al., 2001	908	847	905	855	776	844	879	875	1151	901	899
Riesco et al., 2004	701	678	692	684	708	707	692	672	979	740	738
Rollinson, 1982	611	601	600	606	681	627	612	572	922	664	659
Santosh, 1987	763	730	755	736	797	740	742	697	1042	765	768
Scrimgeour et al., 2001	704	680	694	686	730	694	688	647	969	726	724
Scrimgeour et al., 2005	614	604	603	609	557	609	609	532	864	621	625
Shimura et al., 2002	949	879	947	888	865	899	898	912	1153	910	915
St-Onge et al., 2013		695	713	701	723	708	706	660	982	731	737
Thomas, 2005	519	520	506	525	638	568	543	502	853	609	611
Tong and Wilson, 2006	956	885	955	894	705	882	902	887	1165	915	912
Tsunogae et al., 2007	720	694	711	700	679	702	705	650	976	723	731
Tsunogae et al., 2008	676	657	667	663	680	669	689	652	979	726	731
Wang et al., 2009	650	634	639	640	747	649	643	590	959	681	681
Waters and Whales, 1984	780	743	773	750	773	766	758	741	1033	790	792
Whitney, 1992	773	738	766	745	784	768	763	745	1041	793	803
Yin et al., 2014	896	838	893	845	848	865	871	878	1136	890	902
Yin et al., 2015	1007	925	1008	933	861	933	933	934	1174	939	932
Zeh and Holness, 2003	475	481	462	485	595	515	494	447	804	565	551
Zeh et al., 2004	734	705	725	711	717	716	715	664	987	735	741

To observe the effect of X_{Fe}, X_{Mg} of cordierite and X_{Fe}, X_{Mg}, X_{Mn} & X_{Ca} of garnet on K_D, the data plotted in the form of graph between X_{Fe}, X_{Mg} of cordierite vs K_D and X_{Fe}, X_{Ca}, X_{Mn} & X_{Mg} of garnet on K_D, respectively.

It has been observed that X_{Fe}^{Crd} is showing negative trend line as X_{Fe}^{Crd} = -0.005/K_D + 0.322 with R^2 = 0.009 having a compositional range of 0.0735-0.5958 (mostly between 0.2-0.5) and X_{Mg}^{Crd} is showing gentle positive slope as X_{Mg}^{Crd} = 0.001/K_D + 0.694 with R^2 = 0.000, having a compositional range of 0.0925-0.9238 (mostly between 0.55-0.9).

In the case of garnet, X_{Fe}^{Gt} is showing positive slope as X_{Fe}^{Gt} = 0.016/K_D + 0.524 with R^2 = 0.096, having a compositional range of 0.2948-0.8802 (mostly between 0.5-0.8); X_{Mg}^{Gt} is showing negative slope as X_{Mg}^{Gt} = -0.019/K_D + 0.423 with R^2 = 0.132, having a compositional range of 0.0426-0.6764 (mostly between 0.10-0.40); X_{Mn}^{Gt} is showing gentle positive slope as X_{Mn}^{Gt} = 0.001/K_D + 0.022 with R^2 = 0.008, having a compositional range of 0.0-0.1626 (mostly between 0.01-0.04); X_{Ca}^{Gt} is showing gentle negative slope as X_{Ca}^{Gt} = -0.0/K_D + 0.039 with R^2 = 0.003, having a compositional range of 0.00076-0.0981 (mostly between 0.01-0.05).

A comparison of the calculated LnK_D and 1/T for different geothermometric models has been done. The plots of LnK_D vs 1/T are shown in (Figs. 2a-k).

The data selected in this way was used to check the temperature dependence of the distribution coefficient.

Holdaway and Lee (1977) (Fig. 2a) graph of LnK_D vs 1/T has been plotted as LnK_D= 1611/ T (°C) –0.396 with R^2 = 0.996; temperature occurring within 517-958°C;

Perchuk et al. (1985) (Fig. 2b) as LnK_D = 1623 / T (°C) - 0.392 with R^2 = 0.996 within 485-967°C.

Thompson (1976) (Fig. 2c) as LnK_D=1448/ T (°C) - 0.087 with R^2 = 0.995 within 475-1050°C;

Wells (1979) (Fig. 2d) as LnK_D= 1376/ T (°C) - 0.011with R^2= 0.995 within 462-1053°C;

Aranovich and Podlesskii (1989) (Fig. 2e) as LnK_D =1726/ T (°C) - 0.5with R^2 = 0.988 within 515-976°C;

Dwivedi et al. (1998B) (Fig. 2f) as LnK_D= 1914/ T (°C) – 0.651with R^2= 0.982 within 609-986°C;

Nichols et al. (1992) (Fig. 2g) as LnK_D = 1225/ T (°C) + 0.097 with R^2 = 0.976 within 447-1017°C;

Dwivedi et al. (1998A) (Fig. 2h) as LnK_D = 1968 / T (°C) - 0.724 with R^2 = 0.975 within 551-991°C;

Perchuk (1991) (Fig. 2i) as LnK_D = 1629/ T (°C) - 0.384 with R^2 = 0.969 within 494-964°C;

Kaneka and Miyano (2004) (Fig. 2j) as LnK_D = 2915/ T (°C) – 1.01 with R^2= 0.79 within 719-1232°C and

Bhattacharya et al. (1988) (Fig. 2k) as LnK_D = 1792 / T (°C) – 0.548 with R^2 = 0.661 within 557-930°C.

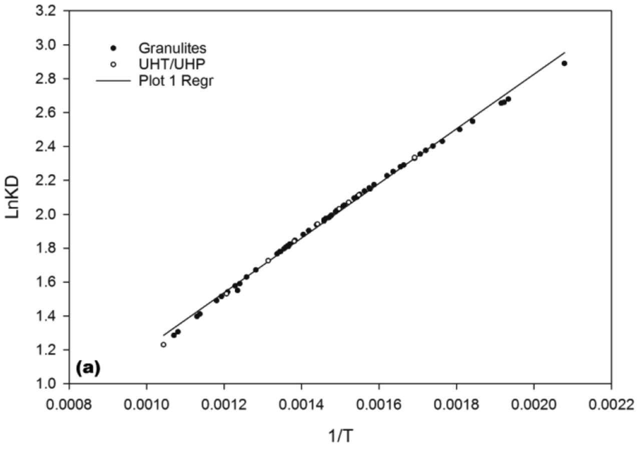

Fig. 2(a): ***LnK_D*** **verses 1/T (Holdaway and Lee, 1977)**

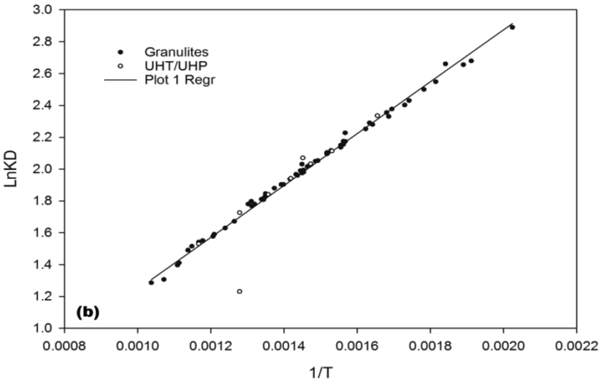

Fig. 2(b): ***LnK_D*** **verses 1/T (Perchuk et al., 1985)**

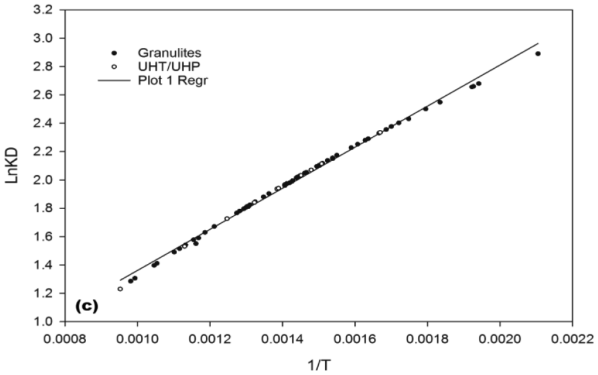

Fig. 2(c): ***LnK_D*** **verses 1/T (Thompson, 1976)**

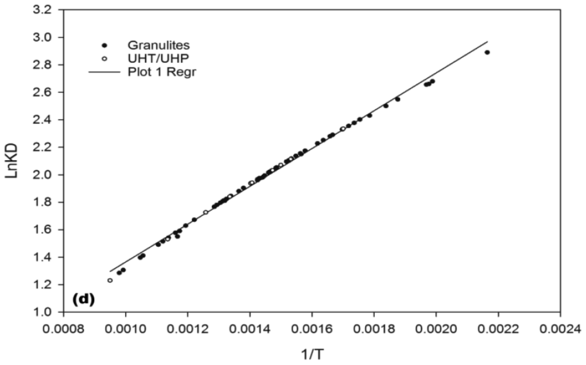

Fig. 2(d): ***LnK_D*** **verses 1/T (Wells, 1979)**

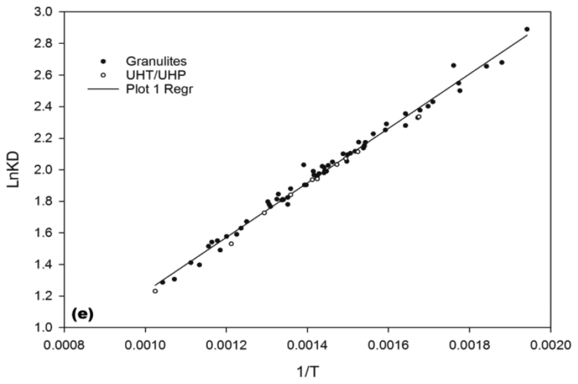

Fig. 2(e): ***LnK_D*** **verses 1/T (Aranovich and Podlesskii, 1989)**

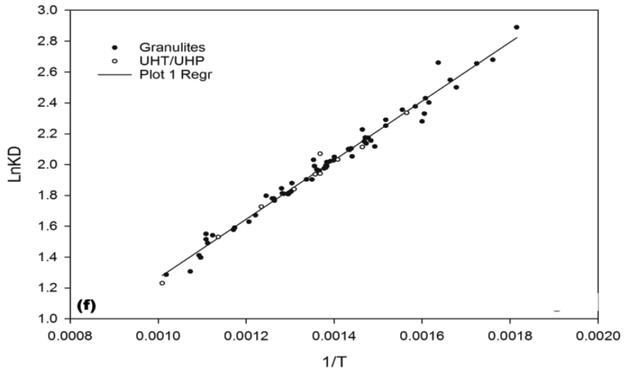

Fig. 2(f): ***LnK_D*** **verses 1/T (Dwivedi et al., 1998B)**

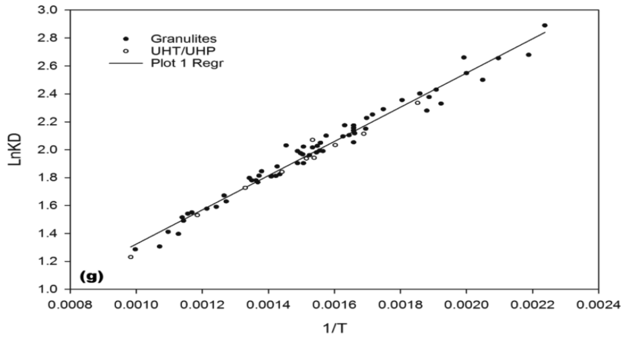

Fig. 2(g): ***LnK_D*** **verses 1/T (Nichols et al., 1992)**

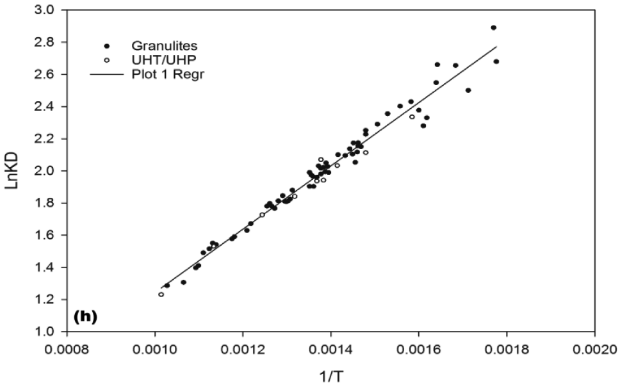

Fig. 2(h): ***LnK_D*** **verses 1/T (Dwivedi et al., 1998A)**

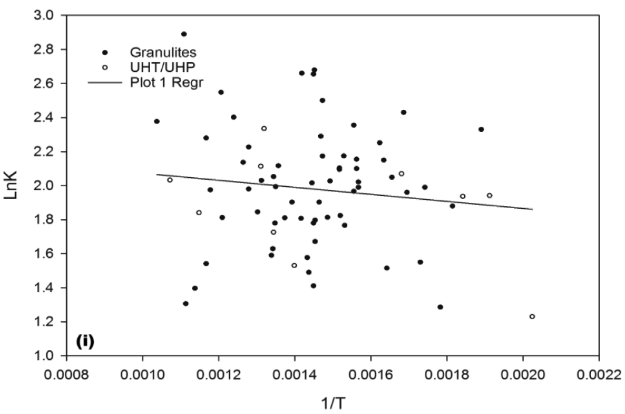

Fig. 2(i): ***LnK_D*** **verses 1/T (Perchuk, 1991)**

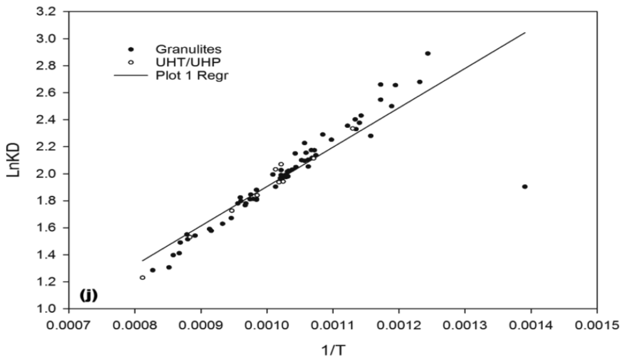

Fig. 2(j): ***LnK_D*** **verses 1/T (Kaneka and Miyano, 2004)**

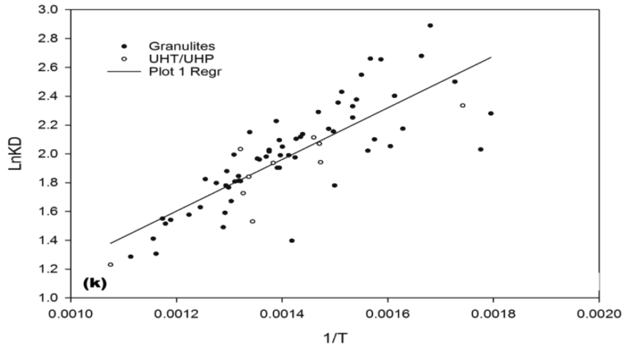

Fig. 2(k): ***LnK_D*** **verses 1/T (Bhattacharya et al., 1988)**

Several criteria have been used since the beginning for the proper evaluation of metamorphic temperature. Use of consensus temperature or the averaging of results from different thermometers gives a very approximate estimate of temperature. Metamorphic temperature should be evaluated using the results of reaction equilibria and independent thermometry in an integrated fashion. While keeping the above considerations in mind, we have attempted to find the accuracy of each thermometer separately based on the relationship of log of compositional dependence and inverse of temperature. The scattering of temperature values leads to low regression values whereas clustering of temperature gives high regression values.

On the basis of different plots, it has been observed that Holdaway and Lee (1977), Perchuk et al., (1985),Thompson (1976),Wells(1979) and Aranovich and Podlesskii(1989) are showing very good relation between LnK_D vs 1/T and maximum points are coming in best fit lines and have high regression values.

CONCLUSIONS

On applying the eleven versions of the garnet - cordierite (Gt-Crd) thermometers to the empirical data collected from literature considered for this comparative study, we conclude that the five GCRD thermometers (Holdaway and Lee 1977; Perchuk et al., 1985; Thompson, 1976; Wells,1979 and Aranovich and Podlesskii, 1989) are nearly equal valid. These models are showing the highest regression values and maximum points are coming in best fit lines. So, these models can be considered as the most appropriate ones to use for the calculation of temperature.

However, Holdaway and Lee (1977) is the best as compared to the other and its regression correlation coefficient value R^2 is close to 1 which indicates that the maximum points are coming in best fit line. Therefore, the temperature value obtained by the Holdaway and Lee (1977) model is more accurate compare to others.

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AUTHOR'S CONTRIBUTIONS

This research was conceptualised and interpreted by H. Thomas, H. Rana and A. Mishra has collected the published data, complied and run through the software, framed the figures and the manuscript text.

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