Metamorphic evolution of the contact aureole of the Jhirkadandi pluton, Sonbhadra district, Mahakoshal mobile belt, central India

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The metamorphic evolution of the contact aureole around the Late Paleoproterozoic Jhirkadandi pluton in the eastern part of Parsoi Formation of Mahakoshal terrain, central India represents three distinct metamorphic zones, characterized by definite mineral assemblages. The contact-metamorphic event produced the peak-metamorphic mineral assemblages Bt + Qtz + Alb + Sil $\pm$ Cd $\pm$ Grt $\pm$ Mus $\pm$ Kfs in the metapelites of inner aureole, Bt + Qtz + And + Mus + Kfs + Plag $\pm$ Cd $\pm$ Chl in middle aureole and Chl + Mus + Bt $\pm$ And + Alb + Qtz $\pm$ Ep + Mt $\pm$ tourmaline in the outer aureole. The estimated P–T conditions based on detailed geothermobarometric calculations in the thermal metamorphosed rocks are 690°C/3.4 kbar, 580 $\pm$ 15°C and 487 $\pm$ 30°C in inner aureole, middle aureole and outer aureole, respectively. The variation in metamorphic condition suggests that the shallow crustal level emplacement of Jhirkadandi pluton is responsible for the overprinting of contact metamorphic assemblages (M₂) in the low grade metapelites (regional metamorphism M₁) of Mahakoshal Group.

1. Introduction

The emplacement of granitic pluton at shallow depth forms a thermal aureole which is associated with textural, chemical and mineralogical changes in wall rock. Such mineralogical and textural transformations are functions of a distance from the contact with the pluton, chemical composition of the country rock, temperature of the intruding magma, composition of coexisting fluid phases and permeability of the wall rock (Norton and Knight 1977; Hanson 1995; Cartwright and Buick 1996; Brocker and Franz 2000; Kusunose *et al.* 2003; Rossetti

et al. 2007). The occurrences of well-developed contact aureoles and their systematic petrological studies have been reported from several localities (Kerrick 1987; Buntebarth 1991; Symmes and Ferry 1995; Kusunose *et al.* 2003; Brocker and Franz 2000; Buriánek and Dolníček 2011), which lead to better understanding the processes with respect to space and time. Although few studies on thermal aureoles in Paleozoic granitoids of the Himalayan fold belt, particularly from the Tethys zone (Thakur 1993; Pognante *et al.* 1990; Steck *et al.* 1998; Vijan *et al.* 2003) and from the Lesser Himalaya of Kumaun region (Das 1985) have been

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carried out, contact aureoles from the peninsular part of Indian subcontinents are relatively least studied. A number of granitic intrusions associated with contact metamorphism have also been reported from the Mahakoshal belt of central India (Srivastava 1969; Nair *et al.* 1995; Roy *et al.* 2002; Kumar 2005) however, none of the works brought details on thermal aureoles and systematic documentation of their geothermobarometry. Through detailed petrographic, mineral chemistry and P–T conditions, we try to fill this gap by providing new constraints on the metamorphic evolution of the thermal aureole of Jhirkadandi pluton in the eastern part of the Mahakoshal Belt.

2. Geological setting

The arc-shaped supracrustal belt constituting the Mahakoshal Group (Nair *et al.* 1995), earlier known as Bijawar Group (Mathur and Narain 1981; Iqballudin and Mohgni 1981), is developed along the southern margin of Bundelkhand Craton. The ‘Mahakoshal Group’ represents a rift basin developed during the Paleoproterozoic in central India (Srivastava *et al.* 2000a, b; Roy 2008). The belt is about 500 km in length and extends from northeast corner of Jabalpur district of Madhya Pradesh along the Son Valley to the border of Palamau, in Jharkhand (figure 1). This belt forms the northern part of the Central Indian Tectonic Zone (CITZ) (Radhakrishna 1989; Acharyya and Roy 2000) and constitutes a part of Son Narmada (SONATA) zone (Ravi Shanker 1993). The

Mahakoshal Group constitutes volcanosedimentary rock sequences of Paleoproterozoic and developed between the Bundelkhand Craton in the north and Chhotanagpur Gneissic Complex of peninsular Indian shield in the south. According to Nair *et al.* (1995) and Srivastava *et al.* (2000a), the Mahakoshal Group comprises of Chitrangi, Agori and Parsoi Formations in ascending order. Subsequently, Kumar (2005) separated out Parsoi Formation from the Mahakoshal Group on the basis of record of polymictic conglomerate (Roy and Devarajan 2000) at its base and considered the Chitrangi and Agori Formations to be part of the Mahakoshal Group of Archaean age. The northern boundary of Mahakoshal belt has sheared relationship with the granite-gneisses of Sidhi block and as faulted contact and at some places angular unconformable contact with the Vindhyan Supergroup (figure 1). The southern part of Mahakoshal Group also has a sheared relationship with granite gneisses of Chhotanagpur block. The Parsoi Formation comprises low grade pelitic metasediments, bluish grey or green in colour with silky lusture with banded or ribbon-like structures, and sometimes with varve-like alternating light and dark gray bands. The arenaceous sediments occur as lenticles and laminae in the main phyllitic mass (Srivastava 1969).

The present study area forms a part of the eastern extremity of the Parsoi Formation of Mahakoshal belt. The Jhirkadandi pluton is lensoidal in shape, trending in the E–W direction with an area extension of ca 20 km². It is exposed near the confluence of Kanhar River with Son River

Figure 1. Regional geological map showing the arch shaped Mahakoshal Group bounded between Son–Narmada south fault (SNSF) and Son–Narmada north fault (SNNF). The abbreviations are: CITZ=Central Indian Tectonic Zone, CIS=Central Indian Suture (after Roy *et al.* 2002).

(figure 2a). The thermal aureole has been studied in the southern part only whereas its northern part is faulted by north Son–Narmada Fault (Srivastava 1969). The Jhirkadandi aureole has average uniform width of 600 m and the main part of aureole is situated between the villages Parach and Nigai where it has maximum width ca 800 m (figure 2b).

The granitoid of Jhirkadandi is interpreted to be hybrid type post-orogenic granitoid, highly metaluminous, transitional between sub-alkaline and calc-alkaline with low initial Sr ratios (Nair *et al.* 1995; Srivastava *et al.* 2000a; Roy 2008; Srivastava and Kumar 2010). Based on the model composition, it is suggested to be composite in character, having

Figure 2. (a) Geological map of the eastern part of Parsoi Formation of Mahakoshal Group showing series of granitoid intrusives, marked by numbers. 1=Jhirkadandi, 2=Baghisoti, 3=Tumia, 4=Rohiniyan, 5=Kumba Khurd, 6=Harnakachar (Kon road) and 7=Harnakachar. (b) Geological map around Jhirkadandi showing the three zones of contact aureole at the southern part of Jhirkadandi pluton (modified after Srivastava 1977).

a granodioritic core fringed by quartz-monzonite, with gradational contact (Srivastava 1977). The less precise Rb–Sr whole rock radiometric ages (1869 ± 180 and 1813 ± 65 Ma, Pande *et al.* 1996; Sarkar *et al.* 1998) and 1753 ± 9 U–Pb zircon SHRIMP geochronological data (Sita Bora and Kumar 2012) indicate a predominant Late Paleoproterozoic intrusion event for the Jhirkadandi pluton.

3. Architecture of the Jhirkadandi aureole

The thermal aureole of the Jhirkadandi pluton is about 600 m wide (figure 3a). The metamorphic rocks in the aureole are mainly metapelites with layers of metapsammites of several mm to cm thickness. Based on the textural and mineralogical associations the aureole has been divided into three parts, viz., inner, middle and outer aureoles/zones. Relics of sedimentary textures are nearly absent in

the inner aureole and occasionally preserved in the middle and frequently observed in outer aureole.

3.1 Country rocks outside the contact aureole

In general, the Parsoi Formation is characterized by low-grade tuffaceous phyllite and metasediments of green-schist facies, occupying the large area between Jhirkadandi to Renukoot of Son valley (Nair *et al.* 1995; Roy *et al.* 2002). Metasediments contain white mica (sericite), chlorite, quartz, albite and sometimes graphite. A metamorphic mineral association of metavolcanics consists chlorite + actinolite + albite + epidote $\pm$ quartz $\pm$ white mica $\pm$ prehnite $\pm$ calcite $\pm$ biotite $\pm$ titanite $\pm$ ilmenite $\pm$ magnetite (Nair *et al.* 1995). Some times the chlorite porphyroblasts (up to 0.9 mm across) are arranged parallel or subparallel to the axial planes of crenulation folds developed which is defined by the mineral assemblage actinolite+epidote+feldspar+quartz+chlorite.

Figure 3. (a) A view of inner and middle aureoles developed near Jhirkadandi village. The granite is light colour while the dark shade represents the middle aureole, (b) the garnet and cordierite showing the hornfelsic texture in the inner zone of aureole near Nigai village, (c) garnet, cordierite and sillimanite bearing hornfelsic rock developed in the immediate vicinity of Jhirkadandi granitoid. The grains of garnet are embedded in the matrix and (d) chlorite-muscovite-biotite bearing thermal metamorphic rock from the outer to middle part of aureole, exposed at the south of Nigai village.

Figure 4. Photomicrograph of the contact metamorphic rocks of the inner, middle and outer aureoles: (a) Sieved garnet (Gt) with quartz and biotite association with cordierite and fibrolite in the matrix of quartz and feldspar from the inner aureole, (b) the coarse grained scarlet brown colour biotite (Bt) associated with coarse grained cordierite (Cd) and andalusite (And) in the inner aureole. Development of fibrolite (Fib) at the rim part of andalusite is also present. Bunches of fibrolite (Fib) with xenoblastic muscovite represents the dehydration reaction and decomposition textures, (c) coarse grained cordierite (Cd) and andalusite (And) associated with scarlet biotite (Bt) from the outer part of inner aureole showing hornfelsic texture. The fibrolite (Fib) is mainly due to decomposition of muscovite (Mus), (d) coarse grained andalusite (And) from middle aureole associated with chlorite (Chl), muscovite (Mus) and biotite (Bt) in the matrix of quartz (Qz) and feldspars (Kfs) from the middle aureole, (e) overprinted texture marked by the development of muscovite and biotite in the matrix of regionally metamorphosed metapelites and (f) development of the andalusite, biotite and muscovite in the pelitic rock of outer aureole where the foliation S_1 , developed during the regional metamorphism is also shown. Bar represents the magnification. Abbreviations: Gt=garnet, Mus=muscovite, Cd=cordierite, Bt=biotite, Ksp=K-feldspar, Sil=sillimanite(fibrolite), Chl=chlorite, q=quartz and Mt=magnetite.

Similarly, presence of medium to fine grained andalusite away from aureoles in the metapelites of Parsoi Formation is an indication of the influence of thermal perturbation on the larger domain as post-tectonic growth (Srivastava 1977) during the M₂ event in the low grade metamorphosed terrain of Parsoi Formation of eastern part (figure 2a).

3.2 Rocks in the contact aureole

The progressive thermal metamorphism of the metapelites with pre-existing foliation resulted in a steady decrease of fissility as the grade progresses (figure 3b and d). The Jhirkadandi aureole constitutes three distinct zones of aureoles, each characterized by specific mineral assemblages and textural and structural characteristics (figure 2, Srivastava 1969; Kumar 2005). The inner aureole with immediate contact with granite is characterised by high temperature minerals such as fibrolite, cordierite and garnet. The transition to the middle aureole, biotite and andalusite exhibit random orientation and decussate texture and the outer aureole have medium to fine grained metasedimentaries with shimmer texture.

3.2.1 Inner aureole (Sil/Fibr-Bt-Crd-Grt zone)

The inner aureole is between 25 and 50 m in width and lies in the immediate neighbourhood of Jhirkadandi pluton. At the immediate contact the mineralogical changes become too frequent and within a short distance the rock show dominance of garnet and fibrolite and are characterized by hornfelsic texture (figure 3b and c). Cordierite and red coloured biotite are the important minerals present. The muscovite is nearly absent and decomposed into fibrolite which demarcates the beginning of this zone. Sometimes the appearance of fibrolite is marked by the phase transformation of andalusite in this zone. The assemblages developed in metapelites are characterized by biotite, cordierite, fibrolite, garnet, K-feldspar, plagioclase, quartz involved mineral phases and are portrayed in AFM diagram (figure 5).

3.2.2 Middle aureole (And-Bt-Mus-Crd zone)

The outer boundary of the middle aureole is characterized by decussate and sporadic granoblastic texture. The andalusite, muscovite and biotite are usually represented by the random orientation

Table 1. Representative electron microprobe analyses of garnet in the inner aureole of the study area along with their structural formula.

NG/2	19	20	21	22	23	24
SiO ₂	36.78	36.68	36.86	36.28	36.76	36.67
TiO ₂	0.00	0.00	0.00	0.00	0.02	0.00
Al ₂ O ₃	21.18	21.12	21.27	21.31	21.13	21.22
Fe ₂ O ₃	0.72	1.56	1.85	1.60	1.82	1.17
Cr ₂ O ₃	0.04	0.00	0.05	0.05	0.00	0.00
FeO	38.42	37.01	37.02	37.07	36.61	38.08
MnO	0.39	0.40	0.41	0.41	0.35	0.30
MgO	2.09	2.90	1.95	3.08	3.01	2.32
CaO	1.08	1.12	1.08	1.15	1.08	1.09
Total	100.71	100.79	100.49	100.95	100.83	100.85
Based on 12 oxygen						
Si	2.971	2.948	2.983	2.916	2.954	2.955
Al ^{iv}	0.029	0.052	0.017	0.084	0.046	0.005
Al ^{vi}	1.987	1.949	1.985	1.935	1.950	2.001
Ti	0	0	0	0	0.001	0
Fe ³⁺	0.064	0.094	0.113	0.097	0.110	0.071
Cr	0.003	0	0.003	0.003	0	0
Mg	0.252	0.347	0.238	0.369	0.359	0.279
Fe ²⁺	2.599	2.488	2.506	2.492	2.454	2.566
Mn	0.026	0.027	0.028	0.028	0.024	0.02
Ca	0.093	0.097	0.094	0.099	0.093	0.094
Almandine mole%	87.5	84.1	87.4	83.4	83.7	86.7
Grossularite mole%	3.1	3.2	3.2	3.3	3.1	3.2
Pyrope mole%	8.5	11.7	8.3	12.3	12.2	9.4
Spessartite mole%	0.9	0.9	1.0	1.0	0.8	0.7

and chlorite is nearly absent. The andalusite-muscovite-biotite $\pm$ cordierite-quartz is the prominent mineral assemblages in the pelitic rocks of this zone (figure 3d). The andalusite appears at the contact is associated with shimmer aggregates in the metapelites towards the peripheral parts.

3.2.3 Outer aureole (Chl-And-Bt zone)

The peripheral part of the aureole comprises mainly of phyllitic rocks with spotted appearance. The rocks are less fissile relative to the country rock. Chlorite, muscovite, biotite, sericite, ilmenite, albite, microcline, andalusite and tourmaline are the important minerals representing this zone. The first mineralogical changes are typified by the segregation of the clay minerals into shimmer aggregate and partial conversion of chlorite into biotite. The rocks of this stage give a spotted appearance and visual sign of diffusion activities in the form of growing up of clots of biotite and shimmers. The random orientation of tiny flaky minerals, viz., chlorite, sericite, and biotite are the

characteristic of this zone. The andalusite of this zone is smaller and consists of tiny inclusion of chlorite and muscovite.

4. Deformation

Three discrete event of metamorphism were distinguished in the metasedimentary rocks surrounding the Jhirkadandi pluton:

- low-pressure and low-temperature regional metamorphism M_1 and deformation D_1 that overprinted primary sedimentary textures;
- relatively low pressure and high-temperature contact metamorphism M_2 , locally accompanied by deformation D_2 ,
- low-pressure and low-temperature retrograde metamorphism M_3 with local development of ductile shear zones D_3 . The last type is least developed and not much focused in the present text.

The earliest recognizable tectonic microstructures are visible in the outer zone of the contact aureole. The metapelite and metapsammite

Table 2. Representative electron microprobe analyses of muscovite mineral in the middle and outer aureoles of the study area along with their structural formula.

Rock type	Middle aureole				Outer aureole	
	T3/C2/5		T3/C2/1		T3/C	
Ref. pt	28	29	79	80	2	8
SiO ₂	46.67	45.56	45.65	47.63	47.52	47.16
TiO ₂	0	0	0.17	2.09	0.04	0.47
Al ₂ O ₃	34.58	33.85	36.64	29.52	36.66	36.83
Cr ₂ O ₃	0	0	0.04	0	0.16	0
FeO	1.03	0.11	1.05	3.91	1.00	1.13
MnO	0.01	0.02	0	0.02	0	0.03
MgO	0.61	0.77	0.38	1.98	0.43	0.50
CaO	0	0.03	0.05	0	0	0.04
Na ₂ O	0.63	0.45	0.62	0.14	0.25	0.72
K ₂ O	8.64	8.61	9.76	9.69	9.40	8.87
Total	92.14	90.38	94.35	94.98	95.43	95.81
Based on 22 oxygen						
Si	6.324	6.244	6.099	6.423	6.234	6.167
Al ^{iv}	1.676	1.756	1.901	1.577	1.766	1.833
Al ^{vi}	3.845	3.834	3.868	3.115	3.903	3.843
Ti	0	0	0.017	0.212	0.040	0.046
Cr	0	0	0.001	0	0.006	0
Mg	0.124	0.160	0.075	0.398	0.084	0.097
Fe ²⁺	0.116	0.130	0.117	0.441	0.110	0.124
Mn	0.002	0.002	0	0.002	0	0.003
Ca	0	0.005	0.007	0	0	0.005
Na	0.164	0.121	0.161	0.037	0.064	0.184
K	1.493	1.539	1.663	1.667	1.573	1.48

contain foliation S_1 defined by the orientation of chlorite and muscovite flakes. The green schist samples from the outcrop near Sarpatwa and south of Parach villages out side the aureole exhibits older folded foliation (S_1) defined by the syn-tectonic mineral assemblage actinolite + albite + epidote $\pm$ quartz $\pm$ chlorite in the mafic rocks and sericite $\pm$ biotite-chlorite $\pm$ epidote-microcline $\pm$ albite-quartz in the pelitic rocks.

Metapelite is the most abundant thermally metamorphosed rock type in the contact aureole which is characterized by the development of cordierite, andalusite, garnet, fibrolite and K-feldspar to andalusite, chlorite and muscovite mineral assemblages from outer to inner. The outer and middle aureoles exhibit random orientation of biotite and andalusite showing decussated texture whereas the inner zone in the immediate neighbourhood of the contact with the granite shows hornfelsic texture (figure 3b and c). These textures are perhaps believed to be indicative of crystallization under the hydrostatic environment during the advanced stage of thermal metamorphism.

5. Metamorphic evolution

5.1 Petrography and mineral chemistry

The metapelitics and metapsammitic rocks involved in the thermal metamorphism around Jhirdadandi granitoid are characterized by presence of andalusite, cordierite, garnet, biotite, chlorite, quartz, plagioclase, K-feldspar, fibrolite and muscovite. Ilmenite, tourmaline, zircon, monazite and pyrite are accessory minerals. Cordierite, garnet and andalusite occur as medium to coarse porphyroblast and showing hornfelsic texture (figure 4). Porphyroblast of cordierite is associated with garnet + fibrolite (figure 4a) or fibrolite + scarlet biotite (figure 4b and c) in the inner aureole without any foliation and biotite + muscovite + andalusite in the middle aureole (figure 4d) with diffuse margins. Andalusite often forms large chistolitic prismatic grains up to 30 mm in length, locally with small inclusions of chlorite, quartz and biotite (figure 4d). The replacement of chlorite into biotite is demarcated in this zone. The inclusions of chlorite, biotite and muscovite in the andalusite

Table 3. Representative electron microprobe analyses of biotite mineral in the inner aureole, middle aureole and enclaves (with in granite) of the study area along with their structural formula.

Sample	Middle		Inner		Enclave				
	T3/C2/1		NG/2		JH/ME1				
Ref. pt	3	4	25	26	18	19	20	23	24
SiO ₂	39.23	41.77	34.30	34.44	37.06	37.48	36.17	37.08	36.64
TiO ₂	1.98	2.47	2.90	3.50	1.98	1.89	1.88	3.05	3.38
Al ₂ O ₃	23.43	29.33	18.34	19.66	14.22	14.17	14.17	13.96	13.98
Cr ₂ O ₃	0.08	0.03	0.14	0.13	0.07	0	0.19	0	0.01
FeO	18.08	7.22	23.39	23.29	18.53	17.28	18.07	17.92	18.77
MnO	0	0.01	0	0	0.38	0.34	0.31	0.29	0.30
MgO	5.23	1.94	7.60	6.55	13.04	13.10	13.01	12.48	11.85
CaO	0.19	0.05	0	0	0.05	0.12	0.10	0.05	0
Na ₂ O	0.12	0.23	0.11	0.12	0.13	0.13	0.10	0.12	0.09
K ₂ O	5.59	7.74	8.45	7.42	8.60	8.91	8.47	9.10	9.15
Total	93.98	90.80	95.23	95.15	94.05	93.39	92.40	94.04	94.16
Based on 22 oxygen									
Si	5.766	5.996	5.321	5.296	5.695	5.765	5.695	5.696	5.653
Al ^{iv}	2.234	2.004	2.679	2.704	2.305	2.235	2.341	2.304	2.347
Al ^{vi}	1.824	2.958	0.674	0.859	0.270	0.334	0.268	0.222	0.194
Ti	0.219	0.266	0.338	0.401	0.288	0.218	0.221	0.352	0.392
Cr	0.003	0.001	0.006	0.005	0.003	0	0.008	0	0
Mg	1.145	0.415	1.757	1.502	2.986	3.002	3.033	2.858	2.725
Fe ²⁺	2.220	0.866	3.035	2.996	2.381	2.222	2.363	2.302	2.421
Mn	0	0.002	0	0	0.049	0.045	0.041	0.038	0
Ca	0.030	0.008	0	0	0.008	0.020	0.016	0.008	0
Na	0.034	0.064	0.034	0.041	0.390	0.038	0.031	0.035	0.027
K	1.048	1.418	1.673	1.445	1.685	1.745	1.69	1.783	1.800
X _{Mg}	0.340	0.324	0.367	0.334	0.556	0.575	0.562	0.554	0.529

and their cross cutting relationship with matrix foliation in metapelites indicate overprinting due to post-tectonic thermal perturbation event.

The easily recognizable tectonic microstructures are visible in the outer zone of the contact aureole in the form of regional foliation of S_1 defined by the orientation of chlorite and muscovite flakes. The green schist rocks from the outcrop near Sarpatwa and south of Parach villages (outside the aureole, figure 2b) exhibit regional metamorphic foliation (S_1) defined by the syn-tectonic mineral assemblage actinolite + albite + epidote $\pm$ quartz $\pm$ chlorite in the mafic rocks and sericite $\pm$ biotite – chlorite $\pm$ epidote – microcline $\pm$ albite–quartz in the pelitic rocks. The regional metamorphic foliation (S_1) and overprinting of thermal texture represented by development of coarse grained andalusite and biotite minerals (figure 4e and f) has been demarcated the beginning of outer zone of thermal metamorphism.

The mineral chemistry of the coexisting mineral phases has been discussed on the basis of representative EPMA data (tables 1–6). The electron probe analyses were carried out at Geological Survey of India (GSI) laboratory in Faridabad

(New Delhi) by CAMECA SX100 electron microprobe. Selected thin sections of approximately 40 μ m coated with carbon were used as targets. For silicate analysis the accelerating voltage was 15 kV with beam current of 10 nA and beam diameter of 1 μ . The standards used for different elements were Al (Al_2O_3), Si, Ca ($CaSiO_3$), Ti (TiO_2), Cr (Cr), Zn (Zn), Na (albite), K (orthoclase), Fe (Fe_2O_3), Mn (Rhodonite), Mg (peridotite), Ba ($BaSO_4$), F (CaF_2), Na (NaCl), P (apatite). The mineral chemistry of the phases is given below:

5.1.1 Garnet

The chemical composition of garnet shows comparatively higher in almandine mole% which varies from 83.40% to 87.50% (table 1). The pyrope mole% (8.30–12.30%) and grossularite mole% (3.10–3.30%) of garnet is low.

5.1.2 Muscovite

The muscovite is recorded from all the zones of aureole. The chemical composition is more or less uniform. The Al_2O_3 composition ranges from 29.52 to 36.82 wt% and comparatively higher in the outer aureole (table 2). The MgO and Cr_2O_3 are very low usually less than 1 wt%. The $\sum X$ is higher (1.82–1.66) in the middle aureoles and low (<1.6) in outer aureole. Similarly the Al^{VI} composition range from 3.8 to 3.1 p.f.u. in the middle and more than 3.8 p.f.u. in the outer aureole.

5.1.3 Biotite

It has variable Ti-content ranging from 2.9 to 3.5 wt% in the inner aureole, and 1.98 to 2.47 wt% in the middle aureole. Their X_{Mg} composition range is between 0.33 and 0.37 in the inner aureole, and 0.32 to 0.34 in middle aureole. The Ti-content of biotite shows a systematic increase from lower to higher temperature from outer to inner aureole (table 3). Alkalies deficiency ($X < 2.0$) is present in the biotite. The deficiency is very high in inner aureole ($\sum X = 0.38–0.03$) and low in middle ($\sum X = 1.20–1.5$) aureole. The Al_2O_3 composition ranges from 18 to 19 wt% in inner aureole, 23 to 29 wt% for middle. Similarly the Al^{IV} composition ranges from 2.68 to 2.70 p.f.u. and 2.0 to 2.23 p.f.u. for inner and middle aureoles, respectively.

5.1.4 Cordierite

The cordierite contains mainly SiO_2 , Al_2O_3 , FeO, and MgO. The $Na_2O + K_2O$ present less than 1%. The X_{Mg} of cordierite ranges from 0.49 to 0.50

Table 4. Representative electron microprobe analyses of cordierite in the inner aureole of the study area along with their structural formula.

Sample	NG/2		
	27	28	31
SiO_2	48.32	48.10	48.40
TiO_2	0.06	0	0
Al_2O_3	33.24	33.25	33.29
Fe_2O_3	0	0	0
Cr_2O_3	0.02	0.06	0.06
FeO	11.43	11.44	11.64
MnO	0.15	0.15	0.03
MgO	6.23	6.50	6.28
CaO	0.04	0.05	0
Na_2O	0.12	0.12	0.17
K_2O	0.02	0.07	0.09
Total	99.54	99.64	99.98
Based on 18 oxygen			
Si	4.976	4.960	4.976
Al	4.042	4.041	4.034
Ti	0.004	0	0
Fe^{2+}	0.986	0.986	1.001
Cr	0.001	0.005	0.005
Mg	0.958	0.998	0.962
Mn	0.013	0.005	0.003
Ca	0.005	0.005	0
Na	0.025	0.023	0.034
K	0.002	0.009	0.012
X_{Mg}	0.493	0.503	0.490

Table 5. Representative electron microprobe analyses of feldspar in the inner aureole, granite and enclaves (with in granite) of the study area along with their structural formula.

Rock Sample Ref. pt	Plagioclase					Orthoclase		
	Inner		Granodiorite			Enclave		
	NG/2		JH/1			JH/ME1		
	32	33	13	17	21			
SiO ₂	59.83	60.36	67.58	65.61	62.79	64.74	63.36	64.59
TiO ₂	0	0	0.05	0	0.03	0	0.06	0.01
Al ₂ O ₃	25.83	25.66	19.83	21.44	23.16	18.65	18.85	18.86
Fe ₂ O ₃	0.05	0.15	0.07	0.36	0.02	0.06	0.011	0.14
MgO	0	0	0.01	0.12	0	0	0	0.02
CaO	6.72	6.65	0.02	1.95	4.00	0	0	0.05
Na ₂ O	7.78	8.02	11.66	9.75	9.32	0.41	0.26	1.20
K ₂ O	0.10	0.11	0.16	0.09	0.10	15.34	15.66	14.21
Total	100.38	100.73	99.54	99.31	99.65	99.20	98.23	99.07
Based on 8 oxygen								
Si	2.656	2.665	2.971	2.895	2.787	2.99	2.975	2.987
Al	1.351	1.338	1.027	1.115	1.212	1.018	1.043	1.028
Ti	0	0	0.002	0	0.001	0	0.002	0
Fe ³⁺	0.002	0.005	0.002	0.012	0.008	0.002	0	0.005
Mg	0	0	0.001	0.008	0	0	0	0.001
Na	0.670	0.680	0.993	0.834	0.802	0.037	0.023	0.108
Ca	0.32	0.312	0.009	0.092	0.19	0	0	0.003
K	0.006	0.006	0.009	0.005	0.006	0.906	0.938	0.838
X _{an}	0.321	0.313	0.009	0.099	0.190			

(table 4) which indicates presence of FeO enriched phase component with respect to Mg end member cordierite.

5.1.5 Plagioclase

In the granitoids of Jhirkadandi, the chemical composition of plagioclase is quite constant (table 5). The anorthite ranges from An₁ to An₁₉ in the granodiorite. The higher anorthite content (An₃₁–An₃₂) is found in the inner aureoles.

5.1.6 Amphibole

The calcic amphibole is present in granitoid rocks with compositional ranges from 4 to 5 wt% for Al₂O₃ (table 6). The Na₂O and FeO are always more than 0.7 wt% and 9 wt%. The X_{Mg} ranges from 0.35 to 0.24.

5.2 Phase relationship and metamorphic reactions

The granitoid pluton causes a high geothermal gradient resulted into the textural and mineralogical changes in a narrow zone. The mineral assemblages of low pressure and low to high temperature conditions from outer to inner aureole

along with textural and mineralogical changes (figure 4) indicate the overprinting of contact metamorphic assemblages in the low grade regional metamorphism. Possible cordierite-producing reactions for metapelites include Mus + Chl + Qtz = Crd + Bt + H₂O in the middle part and Mus + Bt + Qtz = Crd + Kfs + H₂O towards the inner part of the contact aureoles. Andalusite/fibrolite in the inner part is considered to be a product of dehydration reactions that involve mostly the breakdown of muscovite. The beginning of the contact metamorphism in the inner aureole of Jhirkadandi is also marked by the appearance of fibrolite suggests the reaction:

The occurrences of garnet and cordierite along with sillimanite/fibrolite in the inner most part of the aureole of Jhirkadandi can be explained by the reaction in the KFMASH system and is advanced stage of hornfels metamorphism (figure 5).

The development of fibrolite at the margins of andalusite from the inner aureole zone explains the

Table 6. Representative electron microprobe analyses of the chlorite and amphibole minerals in the outer aureole and granite of the study area along with their structural formula.

Sample Ref. pt	Amphibole		Chlorite
	Granitoid		Outer aureole
	JH/2		T3/C2/1
	4	11	32
SiO ₂	51.00	51.97	23.19
TiO ₂	0.17	0.10	3.55
Al ₂ O ₃	4.11	3.29	17.06
Fe ₂ O ₃	4.01	3.51	0
FeO	10.45	9.52	25.46
MnO	0.43	0.54	0
MgO	14.49	15.54	4.50
CaO	12.12	12.46	0.15
Na ₂ O	0.796	0.56	0.08
K ₂ O	0.35	0.14	2.50
Total	97.93	97.54	76.49
Based on	23 oxygen		28 oxygen
Si	7.394	7.501	5.813
Al ^{iv}	0.606	0.499	2.187
Al ^{vi}	0.095	0.061	2.853
Ti	0.018	0.011	0.669
Fe ³⁺	0.425	0.372	0
Mg	3.130	3.343	1.680
Fe ²⁺	1.279	1.158	5.338
Mn	0.053	0.044	0
Ca	1.882	1.926	0.040
Na	0.285	0.181	0.037
K	0.064	0.026	0.798
X _{Mg}	0.710	0.743	0.239

phase transformation of aluminosilicate mineral at lower pressure.

The occurrence of Cd + And + Mus + Bt and Cd + And + Bt + Kfs ± Mus assemblages are thus interpreted as a prograde sequence of the KFMASH model reactions which consume muscovite and generating cordierite, andalusite and K-feldspar at low pressure. Cordierite porphyroblasts contain inclusions of muscovite and chlorite, which indicate formation of cordierite by the reaction:

Andalusite locally includes biotite, muscovite and quartz grains from the matrix. These textures are consistent with prograde andalusite growth. The development of coarse grained andalusite and the presence of Cd + Bt + Mus + Als + Qtz

in the pelitic rocks of the middle aureole of Jhirkadandi can be defined by the following reaction in the KFMASH system (Pattison *et al.* 2002):

The beginning of the outer aureole of contact metamorphism in the Jhirkadandi is marked by the presence of decussate andalusite in the assemblage Bt + Mus + And ± Chl ± Kfs (microcline). The appearance of andalusite due to the decomposition of Mus + Chl in presence of quartz can be explained by following reaction in the KFMASH system (figure 5).

5.3 P–T conditions

The pressure and temperature conditions of metamorphism of the garnet-cordierite-fibrolite-biotite bearing hornfels of inner aureole have been estimated by conventional Fe–Mg garnet-cordierite and garnet-biotite geothermometers and garnet-biotite-K-feldspar-quartz and garnet-mica-plagioclase-quartz geobarometers. Additional sets of independent reactions between mineral end-members were calculated by THERMOCALC v3.1 using the internally consistent dataset of Holland and Powell (1998) and the internally consistent geothermobarometers of Dwivedi *et al.* (1997) and the results are given in table 7. The temperature obtained from garnet-cordierite-fibrolite-biotite hornfels (inner zone) estimates ranges between 650° and 685°C for Grt-Cd and garnet-biotite geothermometry with the exceptionally some higher estimates of 698°–721°C by some geothermometer (see table 7, Ferry and Spear 1978; Dwivedi 1996; Dwivedi *et al.* 1998) and low estimates of temperature 636°–529°C (Dasgupta *et al.* 1991; Nichols *et al.* 1992). The average temperature from Ti content in mica geothermometer proposed by Lal (1991) estimates 661 ± 20°C (inner aureole) to 580 ± 15°C (middle aureole) and 487 ± 30°C (outer aureole). The pressure calculated for garnet-cordierite-fibrolite hornfels using garnet-cordierite-sillimanite-quartz geobarometers for Fe and Mg endmember reactions, varies from 2.05 to 5.83 kbar. The pressure estimates by Thompson (1976) and Wells (1979) are higher compared to other geobarometers (table 7). The pressure estimates from garnet-mica-plagioclase-quartz-geobarometers lie between 1.6 and 2.68 kbar. These conventional methods estimate low pressure, commonly below 4 kbar. The P–T conditions of garnet-cordierite-sillimanite

Figure 5. P–T stability field of outer, middle and inner aureoles along with the temperature of host rock (MGR) and granitoids (JGR) with different reaction curves/line to estimate the P–T conditions of metamorphism. The curved line marked with numbers involved metamorphic reactions discussed in the phase relationship section. The boxes represent the pressure–temperature conditions estimated by geothermobarometry. The triple point (Pattison *et al.* 2002), univariant curve of andalusite and sillimanite and the relationship with observed reaction textures view that metamorphism at Jhirkadandi is low pressure and medium to high temperature. The AFM projections represent the observed assemblages in the concerned zone of aureole of Jhirkadandi. The abbreviations are: g=garnet, mu=muscovite, als=aluminosilicates, and=andalusite, cd=cordierite, bi=biotite, ksp=K-feldspar, Liq=liquid, sill=sillimanite, Pl=plagioclase, q=quartz, MGR: Mahakoshal Group and JGR: Jhirkadandi granitoid.

(fibrolite) bearing rocks from the internally consistent geothermobarometers and internally consistent dataset varies from 690°C/3.4 kbar (Dwivedi *et al.* 1997) to 690°C/4.11 kbar (THERMOCALC v.3.1).

Based on the proposed metamorphic reactions and their stability, a P–T phase diagram is shown in figure 5 which represents the three distinct zone of contact aureole and their wide range of temperature condition within the aureole and its surrounding. The temperature estimated from hornblende–plagioclase thermometry (Holland and Blundy 1994) has been used to characterize the emplacement conditions of the amphibole–biotite granodiorite and enclaves, provide the temperature 634 ± 35 to $650 \pm 25^\circ\text{C}$ respectively. It seems that the emplacement condition of c. 634 ± 35 to $650 \pm 25^\circ\text{C}$ is lower than the peak metamorphic condition of the garnet–bearing assemblages of the inner contact zone (690°C/3.4 kbar), but this discrepancy is difficult to assess in the present uncertainty of the P–T condition derived from THERMOCALC. We would have thought that granitic intrusion is typically emplaced at conditions of about 700–800°C and the estimates of temperature reflects the

cooling temperature during equilibration of mineral phases.

6. Conclusions

The Jhirkadandi pluton consists of amphibole–biotite granodiorite was possibly emplaced at a pressure of c. 2 kbar, equivalent to a depth of c. 7 km into the low grade regionally metamorphosed (M_1) Parsoi Formation of Mahakoshal Group. The contact metamorphism (M_2) at Jhirkadandi occurs as a result of a higher geothermal gradient produced locally around intruding magma. Metapelite, the most abundant rock type of the contact aureole metamorphism is characterized by the development of andalusite, chlorite and muscovite to cordierite, andalusite, garnet, fibrolite and K-feldspar mineral assemblages. Mineral assemblages delineate three metamorphic zones within the contact aureole: outer aureole (Chl–And–Bt zone), middle aureole (And–Bt–Mus–Cd zone) and inner aureole (Sil/Fibr–Bt–Cd–Grt–zone). The internally consistent geothermobarometry estimates the 690°C/3.4 kbar for the thermal peak of contact metamorphism in the

Table 7. Pressure and temperature estimates of the contact aureole and surrounding granite including enclaves using conventional geothermobarometers and internally consistent dataset.

Rock type	Aureole			Granite	Enclaves
	Inner	Middle	Outer		
Estimate of geothermometers					
	Gt-Cd	Gt-Bt	Ti content of Biotite		
A	665	688			
B	650	721			
C	652	637			
D	655	529			
E	674	685			
F	636	677			
G	698	670			
H	705	680			
I			661 ± 20	580 ± 15	487 ± 30
J					634 ± 35
Estimate of Geobarometers					
Garnet-cordierite-sillimanite-quartz geobarometer					
	P-Mg	P-Fe			
a	5.83	5.19			
b	5.96	5.0			
c	2.33				
d	2.41	2.05			
Garnet-mica-plagioclase-sillimanite-geobarometer					
e	2.58				
f	2.68				
g	1.6				
Result of internally consistent geothermobarometry					
X	690/4.1 Kbar				
Y	690°C/3.4 Kbar				

Note: In Gt-Cd, A=Thompson (1976), B=Perchuk *et al.* (1985), C=Bhattacharya *et al.* (1992b), D=Perchuk (1991), E=Aranovich and Podlesskii (1983), F=Nichols *et al.* (1992), G=Dwivedi (1996), H=Dwivedi *et al.* (1998); I=Lal (1991), J=Holland and Blundy (1994). In Gt-Bt, A=Thompson (1976), B=Ferry and Spear (1978), C=Perchuk *et al.* (1985), D=Dasgupta *et al.* (1991), E=Aranovich *et al.* (1988), F=Bhattacharya *et al.* (1992a), G=Holdaway (2000), H=Dwivedi *et al.* (2007); a=Thompson (1976), b=Wells (1979), c=Perchuk *et al.* (1985), d=Nichols *et al.* (1992), e=Kozioł and Newton (1988), f=Hoisch (1990), g=Wu *et al.* (2004). X=Thermocalc (Holland and Powell 1998), Y=Dwivedi *et al.* (1997).

inner aureole of the Jhirkadandi. The metamorphic temperatures based on different geothermometers are $487 \pm 30^\circ\text{C}$ in the outer aureole, $580 \pm 15^\circ\text{C}$ in the middle aureole and $661 \pm 20^\circ\text{C}$ in the inner aureole at pressures between 1.6 and 2.58 kbar represent agreement of gradual thermal perturbation at shallow depth in the width between 600 and 800 mt across the Jhirkadandi pluton.

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