Identification of paleosols in the Precambrian metapelitic assemblages of peninsular India – A major element geochemical approach

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Al₂O₃ greater than 20%, positive correlation between Al₂O₃ and TiO₂, plot towards the Al₂O₃ corner in the Al₂O₃-K₂O-Fe₂O₃ (T) diagram and high chemical indices of alteration and weathering (CIA, CIW) distinguish the paleosols (fossil residual soils) from transported and deposited pelitic rocks like shales. Submarine weathering products are characterized by high MgO whereas the subaerial ones are not. Application of these criteria shows that majority of the khondalites of Orissa, Andhra Pradesh and Kerala are metamorphosed paleosols. They were probably formed from bauxite type lateritic soils. The protoliths of khondalites of Madras were, however, shales. Except for the biotite schists, other high alumina metapelites of Holenarasipur greenstone belt could also have been formed from paleosols. These latter being characterized by higher MgO content could represent metamorphosed submarine weathering products. The metapelites occurring at the base of the Aravalli Supergroup in Rajasthan also have chemical characters similar to residual soils. The Dharwar and Cuddapah shales stand apart from such metamorphosed probable paleosols.

STUDY of paleosols has played a key role in understanding the Precambrian atmospheric evolution and in deciphering palaeoclimatic conditions. Reports of paleosols from the metamorphosed Precambrian sequences of India have been rare. Sharma interpreted the pyrophyllite-diaspore deposits of the low grade metamorphosed Palar Formation of the Precambrian of Bundelkhand province as a paleosol. Golani considered that the sillimanite-corundum deposits of Sonapahar in the Precambrian of Meghalaya may have resulted by high grade metamorphism of lateritic bauxites. Recognition of paleosols in deformed and metamorphosed Precambrian sequences is difficult because in such instances original field relations are modified, the physical fabric of the soil has been destroyed and clay minerals formed during weathering have all been metamorphically recrystallized. To help identifying paleosols in metamorphic terrains, several geochemical criteria have therefore been tried. Reimer suggested that metapelitic rocks with Al₂O₃ greater than 20% may represent paleosols. Taking advantage of K₂O depletion and enrichment of R₂O₃ constituents that accompanies weathering, he further used A–K–F (Al₂O₃–K₂O–Fe₂O₃) diagrams to distinguish transported clayey sediments from paleosols. Maynard observed that TiO₂ and Al₂O₃, the two most insoluble major oxides, can be useful as indicator elements for distinguishing in situ soil profiles from allochthonous sediments. Feakes et al. observed a positive correlation of TiO₂ with Al₂O₃ in Ordovician paleosols of Nova Scotia, Canada. We verified this relation for the data available on the paleosols from the Mt. Vulture Volcano of Italy, the Dominion Reef, Pongola and the Hekpoort of South Africa as well as the Pronto and Athabaska of Canada. In all cases we observed positive correlation between TiO₂ and Al₂O₃. Correlation coefficient appears to be high for high alumina paleosols and moderate for others. By contrast, the metamorphosed shales either do not show any correlation or sometimes exhibit even a negative correlation between TiO₂ and Al₂O₃. This is attributed to differential mobility of these two oxides in the transporting media.

Soil profiles characterized by high degree of weathering are enriched in hydrous clay mineral phases which, with partial desiccation, offer resistance to transport unlike the soil profiles which have witnessed partial argillitic alteration. Perhaps it is for this reason, we notice in river sands feldspar grains which are in various stages of alteration. From this, it may be inferred that the residual clays may be characterized by much higher indices of chemical weathering such as Chemical Index of Alteration (CIA = 100(Al₂O₃)/(Al₂O₃ + silicate CaO + Na₂O + K₂O)) proposed by Nesbit and Young and Chemical Index of Weathering (CIW = 100(Al₂O₃)/(Al₂O₃ + silicate CaO + Na₂O)) proposed by Harlois.

Although weathering is dominant in subaerial environment, alteration of basalts on the seafloor has also been documented. Submarine alteration could be due to either sea water-rock interaction or alteration brought about by hydrothermal solutions connected with submarine volcanoes. Retallack suggested that in the alteration affected by hydrothermal solution, MgO of the parent material is largely retained unlike in subaerially weathered mafic igneous rocks and these alteration
Table 1. Compositional parameters of Precambrian metapelites of peninsular India useful for identification of palaeosols

<table>
<thead>
<tr>
<th>Rock type &amp; area</th>
<th>$\text{Al}_2\text{O}_3$</th>
<th></th>
<th>$\text{TiO}_2$</th>
<th></th>
<th>CIA</th>
<th></th>
<th>CIW</th>
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<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Avg</td>
<td>Range</td>
<td>Avg</td>
<td>Range</td>
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<td>Range</td>
<td>Avg</td>
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<tr>
<td>Khondalites of Eastern Ghats</td>
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<tr>
<td>Orissa ($n=66$)</td>
<td>8.92–36.33</td>
<td>18.85</td>
<td>0.03–2.25</td>
<td>1.01</td>
<td>68.46–98.94</td>
<td>85.73</td>
<td>79.36–99.83</td>
<td>95.40</td>
</tr>
<tr>
<td>Araku ($n=16$)</td>
<td>12.56–29.76</td>
<td>22.57</td>
<td>0.35–2.35</td>
<td>1.20</td>
<td>61.20–93.91</td>
<td>84.71</td>
<td>71.30–94.38</td>
<td>90.36</td>
</tr>
<tr>
<td>Ibrahimpetnam ($n=8$)</td>
<td>13.73–20.25</td>
<td>16.66</td>
<td>0.15–0.95</td>
<td>0.67</td>
<td>65.50–79.90</td>
<td>70.77</td>
<td>76.77–90.77</td>
<td>83.09</td>
</tr>
<tr>
<td>Madras ($n=10$)</td>
<td>7.50–14.60</td>
<td>11.53</td>
<td>0.03–0.87</td>
<td>0.37</td>
<td>58.90–98.47</td>
<td>76.21</td>
<td>79.30–98.65</td>
<td>88.55</td>
</tr>
<tr>
<td>Kerala ($n=4$)</td>
<td>15.00–20.20</td>
<td>16.80</td>
<td>0.15–0.70</td>
<td>0.57</td>
<td>63.99–74.22</td>
<td>68.29</td>
<td>80.77–88.71</td>
<td>81.20</td>
</tr>
<tr>
<td>Metapelites of Dharwar greenstone belts</td>
<td></td>
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<tr>
<td>Holenarasapur ($n=10$)</td>
<td>6.40–33.20</td>
<td>22.83</td>
<td>0.23–0.82</td>
<td>0.62</td>
<td>77.77–85.21</td>
<td>81.09</td>
<td>95.26–98.76</td>
<td>96.18</td>
</tr>
<tr>
<td>Tnallahalli ($n=8$)</td>
<td>11.81–30.11</td>
<td>19.91</td>
<td>0.49–1.09</td>
<td>0.74</td>
<td>70.50–86.48</td>
<td>79.84</td>
<td>83.74–99.88</td>
<td>92.33</td>
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<tr>
<td>Holenarasapur ($n=6$)</td>
<td>12.15–25.62</td>
<td>19.18</td>
<td>0.48–0.68</td>
<td>0.61</td>
<td>70.23–84.10</td>
<td>77.95</td>
<td>79.20–93.59</td>
<td>88.16</td>
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<tr>
<td>Kallu ($n=7$)</td>
<td>17.96–24.23</td>
<td>20.95</td>
<td>0.83–0.98</td>
<td>0.89</td>
<td>62.62–71.66</td>
<td>69.24</td>
<td>70.55–84.58</td>
<td>79.53</td>
</tr>
<tr>
<td>Holenarasapur ($n=8$)</td>
<td>7.17–17.56</td>
<td>13.15</td>
<td>0.26–0.63</td>
<td>0.45</td>
<td>65.89–89.97</td>
<td>79.11</td>
<td>71.59–93.59</td>
<td>88.16</td>
</tr>
<tr>
<td>Chinnapuran ($n=4$)</td>
<td>14.85–17.77</td>
<td>15.19</td>
<td>0.60–0.68</td>
<td>0.65</td>
<td>67.05–69.80</td>
<td>69.38</td>
<td>74.98–76.13</td>
<td>76.88</td>
</tr>
<tr>
<td>Dharwar ($n=5$)</td>
<td>11.88–12.42</td>
<td>12.10</td>
<td>0.47–0.86</td>
<td>0.66</td>
<td>75.46–87.28</td>
<td>81.24</td>
<td>76.12–95.39</td>
<td>87.80</td>
</tr>
<tr>
<td>Cuddapah ($n=3$)</td>
<td>8.97–17.77</td>
<td>14.66</td>
<td>0.24–0.82</td>
<td>0.60</td>
<td>71.90–76.99</td>
<td>74.26</td>
<td>91.32–99.23</td>
<td>96.59</td>
</tr>
<tr>
<td>Metapelites of Aravalli sequence</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Debari ($n=8$)</td>
<td>9.93–28.96</td>
<td>17.73</td>
<td>0.38–1.27</td>
<td>0.75</td>
<td>53.34–68.87</td>
<td>61.69</td>
<td>77.22–86.13</td>
<td>84.59</td>
</tr>
<tr>
<td>Girwa ($n=15$)</td>
<td>11.29–30.22</td>
<td>17.82</td>
<td>0.02–1.12</td>
<td>0.61</td>
<td>55.88–72.05</td>
<td>72.05</td>
<td>79.95–85.82</td>
<td>83.66</td>
</tr>
<tr>
<td>Jharol argillites ($n=6$)</td>
<td>11.87–25.33</td>
<td>22.77</td>
<td>0.52–0.81</td>
<td>0.61</td>
<td>71.07–76.05</td>
<td>74.55</td>
<td>87.50–91.31</td>
<td>89.01</td>
</tr>
<tr>
<td>(i) Low grade ($n=6$)</td>
<td>35.32–31.61</td>
<td>33.47</td>
<td>1.54–1.87</td>
<td>1.71</td>
<td>75.44–75.70</td>
<td>75.57</td>
<td>89.19–89.72</td>
<td>89.45</td>
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<tr>
<td>(ii) High grade ($n=2$)</td>
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Figure 1. Sketch map of India showing the locations of metapelites whose compositions have been examined for identifying the possible palaeosols.

In the light of the foregoing, we examine the compositions of about 300 Precambrian metapelites from peninsular India to ascertain which of them could probably represent palaeosols. The database includes 117 chemical analyses of khondalites from the Eastern Ghats granulite belt, 157 metapelites from the Dharwar greenstone belts and 40 metapelites from the Aravalli belt (Figure 1). Data of a few shales from Cuddapah sequence also have been examined. References for the sources of data along with the critical parameters ($\text{Al}_2\text{O}_3$, $\text{TiO}_2$, CIA & CIW) are given in Table 1.

$\text{Al}_2\text{O}_3$ content

The khondalites whose analyses have been examined here are from Orissa, Andhra Pradesh (Araku valley and Ibrahimpetnam), Madras and Kerala regions. Forty-two per cent of the analyses of the Orissa and Araku valley khondalites are characterized by $\text{Al}_2\text{O}_3$ content greater than 20%, and the rest from this region have $\text{Al}_2\text{O}_3$ ranging between 15 and 20%. Khondalites of Ibrahimpetnam and Kerala show $\text{Al}_2\text{O}_3$ content ranging...
from 13.73 to 20.20%. The Madras khondalites have the lowest \( \text{Al}_2\text{O}_3 \) falling in the range of 7.50 to 14.60%.

The metapelitic rocks of the Dharwar greenstone belts, barring rare exceptions like those of Holenarasipur schist belt have low \( \text{Al}_2\text{O}_3 \) content. Twenty-five per cent of the Dharwar metapelites, almost all from the Holenarasipur schist belt are characterized by high \( \text{Al}_2\text{O}_3 \). Similarly shales of Cuddapah have low \( \text{Al}_2\text{O}_3 \) ranging from 7.80 to 17.86%. More than 44% of argillites from the Aravalli belt are of high \( \text{Al}_2\text{O}_3 \) type. Argillites of Jharol region appear to be enriched in \( \text{Al}_2\text{O}_3 \) compared to the argillites of Girwa valley and Debari areas.

**\( \text{Al}_2\text{O}_3 \) and \( \text{TiO}_2 \) correlation**

Figure 2 is the \( \text{Al}_2\text{O}_3 \) vs \( \text{TiO}_2 \) plot for the various metapelites of peninsular India. The khondalites of Orissa, Araku valley, Ibrahimpatnam and Kerala exhibit a strong positive correlation between \( \text{Al}_2\text{O}_3 \) and \( \text{TiO}_2 \) \( (r = +0.6348, +0.7720, +0.6273 \) and \(+0.8127) \). Madras khondalites, by contrast show a strong negative correlation \( (r = -0.7883) \).

Except for the biotite schists \( (r = 0.0660) \), strong positive correlation \( (r = +0.9007 \) and \(+0.9529) \) characterizes the high alumina metapelites of Holenarasipur.

**Figure 2.** \( \text{Al}_2\text{O}_3 \) vs \( \text{TiO}_2 \) plot for some of the Pre cambrian metapelites of peninsular India.
and Tividahalli areas of the Holenarasipur greenstone belt. Similarly a strong positive correlation is observed in the Debari argillites, whereas it is moderate and weak in the case of Jharol and Girwa valley argillites of the Aravalli belt. The shales of Dharwar, psammopelites of Aladahalli as well as Cuddapah shales show a depletion of TiO$_2$ with increase in Al$_2$O$_3$.

**A–K–F diagrams**

It can be seen in the A–K–F diagram that the khondalites of Orissa and Araku valley plot in the zone of residual clays (Figure 3a). But the other khondalites including Ibrahimpatnam, Madras and Kerala fall outside the field of residual clays being enriched in K$_2$O (Figure 3b). Some of the Madras khondalites plot on the Al$_2$O$_3$–Fe$_2$O$_3$ join and more towards Fe end due to the enrichment of Fe$_2$O$_3$. In all these cases while the R$_2$O$_3$ (especially Al$_2$O$_3$) constituents are enriched, MgO is depleted.

High alumina metapelites of the Holenarasipur greenstone belt comprising the Holenarasipur and Tividahalli schists plot in the field of residual clays (Figure 3c), some of them as well as the Karli schists from this belt are enriched in K$_2$O and therefore plot outside the field of residual clays. The high alumina schists of Holenarasipur, unlike the residual clays resulting from subaerial weathering, show retention of MgO ranging from 1.66 to 5.42. The biotite schists of Holenarasipur, although characterized by moderate to high alumina, plot outside the field of residual clays. The psammopelites of Aladahalli are enriched in iron compared to the Holenarasipur metapelites, and therefore show a scatter towards F corner of the A–K–F diagram (Figure 3d). The Dharwar and Cuddapah shales plot in the field of normal shales.

Bhattacharya$^{15}$ observed that the Debari paleosol and the associated argillites have compositions different from residual clays. These and the Girwa valley argillites are enriched in K$_2$O. Jharol argillites are stated to have residual clay compositions.

**Weathering indices**

**Chemical index of alteration (CIA)**

The Orissa khondalites are characterized by very high CIA values as in highly weathered soil profiles (avg. 85.73). More than 40% of the Orissa khondalites show CIA values greater than 80 and 30% show this index greater than 90. Similarly the Araku valley khondalites are also characterized by very high CIA (avg. 84.71). Fifty per cent of samples show CIA greater than 85 and 44% of samples, greater than 90. Compared to these, the khondalites of Ibrahimpatnam show a range of CIA values varying between 65.5 and 79.9, average being 70.77 which is not outside the range of shales. The Kerala khondalites also have moderate CIA values.
ranging between 63.00 and 74.22, average being 68.29. In the case of Madras khondalites extreme variation of CIA from 58.9 to 98.47 has been observed. This is due to the large variation of alkali content in these khondalites.

The CIA values of the Dharwar metapelites show a wide range. The high aluminous metapelites of Holenarasipur in spite of their high Al₂O₃ nature show a moderate range of CIA values varying between 70.5 and 85.21. This is due to their high K₂O content. The shales of Dharwar area show a range between 62.16 and 71.88. The metapelites of Aladahalli, Karnataka exhibit CIA values ranging between 75.46 and 87.28. The shales of Cuddapah sequence show a range between 71.90 and 76.99 typical of sedimentary shales. The Debari, Jharol and Girwa valley meta-argillites show a low to moderate range of CIA values varying between 53.34 and 76.05 although they are rich in Al₂O₃.

Chemical index of weathering (CIW)

Since many soil profiles as well as shales undergo diagenetic changes, their alkali content, especially the K₂O content, has been found to be altered² in the case of metapelites post-metamorphic hydrothermal alteration also could contribute to the enrichment of K₂O (ref. 17). Therefore, Harnois¹³ considers that the alteration index calculated on K₂O-free basis will represent better the intensity of weathering. The revised index is designated as Chemical Index of Weathering (CIW). Condie¹⁸ considers CIW as a best measure of intensity of chemical weathering.

The CIW just as CIA values is found to be maximum for khondalites of Orissa (avg. 95.40 and range 79.36–99.83) and Araku valley (avg. 90.36 and range 71.30–94.38). However, the Madras khondalites which show low CIA values are characterized by high CIW (avg. 88.55) suggesting that the low CIA may be due to post-depositional enrichment of K₂O in these khondalites. The Ibrahimpatnam and Kerala khondalites exhibit lower CIW (avg. 83.09 and 81.20 respectively) when compared to the other khondalites.

Although the high alumina Holenarasipur metapelites are characterized by a moderate range of CIA values, they exhibit very high CIW values ranging between 83.49 and 99.89, suggesting post-depositional K₂O enrichment. The biotite schists of Holenarasipur are an exception in having lower CIW (avg. 79.53). The iron-enriched metapelites of Aladahalli similar to the high alumina metapelites exhibit high CIW (avg. 87.80). CIW of the Dharwar shales matches with their low CIA values. Despite their moderate CIA the Cuddapah shales are characterized by high CIW ranging between 91.32 and 99.23. In the Aravalli sequence, the argillites of Girwa valley, Jharol and Debari exhibit moderate values of CIW ranging between 77.22 and 91.31.

Discussion

The high Al₂O₃ content, strong positive correlation of TiO₂ with Al₂O₃, the A–K–F ratios similar to residual soils, low potassic nature and high values for CIA and CIW indicate that the protoliths of the khondalites of Orissa and Araku valley were of the nature of paleosols. Similarity of their compositions with the aluminous laterites of Brazil has also been suggested by Dash et al.¹⁹ The Ibrahimpatnam and Kerala khondalites in respect of having moderately high content of Al₂O₃, and positive correlation of Al₂O₃ with TiO₂ also could have been paleosols. However, higher K₂O content in them indicates that if indeed these were lateritic soils like the Orissa khondalites, they have later been affected by K-metasomatism. Granitization of khondalites in various parts of the Eastern Ghats and the southern Indian granulite terrain has been known for a long time (cf. Krishnan²⁰, p. 108). Because of higher K₂O content the Kerala and Ibrahimpatnam khondalites plot outside the field of residual clays in A–K–F diagram. The Madras khondalites seem to be different from the other khondalites in respect of having low Al₂O₃, negative correlation of TiO₂ with Al₂O₃ and higher K₂O content. They also plot outside the field of residual clays in A–K–F diagram. In all these respects their composition seems to be similar to those of transported argillitic sediments rather than residual soils. We, therefore, consider that the protoliths of khondalites comprised residual laterites as well as sedimentary shales.

High alumina metapelites from the Holenarasipur greenstone belt in respect of their Al₂O₃ content, strongly positive Al₂O₃ and TiO₂ correlation and very high CIW values are similar to paleosols. Unlike the paleosols produced by subaerial weathering they do not show MgO depletion. In this respect they resemble submarine weathering products. Kimberly²¹ suggested the possibility of formation of these clays by alteration associated with volcanic exhalations. The biotite schists of this belt, however, differ from the associated high alumina schists in respect of very low correlation coefficient between Al₂O₃ and TiO₂ and lower CIA and CIW values; they also plot outside the field of residual clays. Their protolith may be a transported pelitic sedimentary rock. However, they have high Al₂O₃ than in normal shales. But as in the case of some khondalites and Precambrian paleosols of other regions, the Holenarasipur metapelites are characterized by higher K₂O content, which renders the composition of these rocks to plot in the field outside that of residual clays in the A–K–F diagram. However, breakdown of high alumina silicate minerals like kyanite to sericite and/or paragonite noticed in these rocks at several places point to K and/or Na metasomatic alteration.

Shales of the Dharwar area, Cuddapah and metapelites of the Aladahalli formation are all characterized by less than 20% Al₂O₃, negative correlation of TiO₂ with
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Al₂O₃, lower CIA values and plot outside the field of residual clays indicating that their pelitic protoliths were lithified sediments which had been transported from the site of weathering.

The Debari argillites of Aravalli mountain belt located close to the interface of granite gneiss (Banded Gneissic Complex) and the Aravalli Supergroup, are characterized by moderate Al₂O₃ content, a strong positive correlation between Al₂O₃ and TiO₂ and moderate values for CIA and CIW. These indicate that they could probably be paleosols. Weak correlation between Al₂O₃ and TiO₂ and their occurrence in the heart of sedimentary sequence above the base of Aravalli belt rule out the possibility of Girwa valley argillites being paleosols. The Jharol argillites exhibit high Al₂O₃, moderate positive correlation between Al₂O₃ and TiO₂, moderate CIA values and high CIW values similar to paleosols. Their plot in the zone of residual clays in the A–K–F diagram corroborates such an inference. However, their occurrence well within the sedimentary sequence of Aravalli mountain belt contradicts this inference. Further studies are essential to understand the reasons for their chemical characteristics. All the meta-argillites of Aravalli sequence are characterized by higher alkali content which may be attributed to the post-depositional alkali enrichment.

Conclusions

Application of criteria such as Al₂O₃ content, Al₂O₃–TiO₂ ratios, A–K–F proportions, chemical indices of alteration (CIA and CIW) and MgO retention has led to identification of the following rock formations as having resulted by the metamorphism of paleosols: 1. Khondalites of Orissa and Araku valley; 2. Metapelites of the Holenarasipur greenstone belt except for the biotite schists; these however could be submarine alteration products; 3. Debari argillites of the Aravalli mountain belt.

Although it is possible that some of the khondalites such as Kerala and Ibrahimpatnam could be paleosols, their original alkali content, especially the K₂O content has largely been altered by post-depositional processes. This is also true for the metapelites of Holenarasipur and Aravalli belts.

Detailed studies could be directed towards some of these occurrences which potentially are metamorphosed Precambrian soil profiles for understanding the Precambrian exogenic processes.

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ACKNOWLEDGEMENTS. This work has been supported by CSIR Junior Research Fellowship to B S We are grateful to Dr K. Gopalan for going through the manuscript and making helpful suggestions, to the Director, NGRI, for encouragement and permission to publish this paper.

Received 17 August 1993, revised accepted 4 April 1994