Journal of Climate Change, Vol. 7, No. 1 (2021), pp. 1-11.
DOI 10.3233/JCC210001

Permo-Carboniferous Climate Change: Geochemical Evidences from Lower Gondwana Glacial Sediments, Rangit Valley, Sikkim Lesser Himalaya, India

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Received July 18, 2020; revised and accepted January 10, 2021

Abstract: The Rangit Gondwana Basin of Sikkim in the lesser Himalaya witnessed a wide span of climate change during the Permo-Carboniferous period. The principal objective of the present study is to document this Permo-Carboniferous climate change in the form of a geochemical signature preserved in the siliciclastic facies of the Rangit Pebble Slate Formation. The stratigraphic sequences of the Rangit Gondwana Basin are categorically well defined and subdivided into upper and lower sequences on the basis of their depositional environment. The lower sequences of the Rangit Gondwana basin are comprised of massive diamictite with large stromatolitic dolomite boulders and dropstone embedded in the coarser sandstone which indicate the cold glaciomarine environment of deposition, whereas upper sequences consist of repeated alternate beds of sandstone, black shale and coal seam with a regular interval depicting the fluvial and deltaic environment of deposition. The enrichment of SiO_2, Al_2O_3, TiO_2, MnO, MgO, and K_2O indicates that these sediments were mostly derived from felsic rock source areas. Chemical Index of Alteration (CIA) and Index of Compositional Variability (ICV) CaO + Na_2O + K_2O/Al_2O_3, and SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) values suggest that the sediments maturity and paleoclimatic environment deposition of the sediments of lower sequences was cold and semi-humid whereas the deposition of sediments of upper sequences was warm and humid. The A-CN-K ternary plot and CIA vs ICV binary plot also indicate and verify that the source areas were subjected to prolonged intense chemical weathering from low to high grade due to shifting of cold to warm humid paleo-climatic condition.

Keywords: Climate change; Geochemistry; Provenance; Rangit Gondwana Basin; Sikkim.

Introduction

The Late Paleozoic Ice Age (LPIA) is considered one of the significant episodes of Permo-Carboniferous climate change on the earth which has been recorded and documented in almost every continent in the form of glacial and post-glacial sea-transgressive lithofacies (Eyles, 1993; Gamundi, 2010; Histon et al., 2013). The Permo-Carboniferous Himalayan Peri-Gondwana sedimentary sequences are well developed across the entire Himalayan countries i.e. China, India, Pakistan, Nepal and Bhutan. In Gondwana master basin of peninsular India, it is characteristically categorized into Upper and Lower Group of Gondwana sequences which are also known as Damuda Group. The sedimentary sequences of the Lower Gondwana Group are characterized by diamictite/tillites, sandstone and shale facies which were derived from glacio-fluvial and/or glacio-marine sedimentation. Whereas, the Upper Gondwana Group shows the deposition of sandstone, shale and interbedded coal sequence which indicate fluvial,

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lacustrine and marine paleo-depositional environment (Mukhopadahya and Bhattacharya, 1996; Ghosh et al., 2004). The Lesser and Tethyan Himalayan sequences of Kashmir, Himachal Pradesh, Arunachal Pradesh and Sikkim also have the Gondwana sedimentary deposits with identical depositional environmental conditions (Raichaudhari, 2002; Rashid and Ganai, 2015; Priya et al., 2019; Mahanta et al., 2020). In the present paper, Gondwana sedimentary successions of Rangit Gondwana Basin (RGB) and the Sikkim Himalaya have been taken into consideration for the study of climate change during the Permo-Carboniferous period. Rangit Gondwana Basin of Sikkim Lesser Himalaya witnessed global climate change from cryospheric/glacial to warm humid environment. The authors have used the normalised major oxides elements for the interpretation of provenance and paleoenvironment of sedimentation. The Chemical Index of Alteration (CIA), Index of Compositional Variation (ICV), paleo-redox condition and weathering trend have been used as a tool for the evaluation of paleoclimatic conditions in the study area. Based on the geochemical evidence, an attempt has been made to reconstruct the climate-stratigraphy of the Permo-Carboniferous sediments of Sikkim Lesser Himalaya.

Geochemical Investigations

A total of thirty (30) fresh samples of sandstone and shale were systematically collected from Permo-Carboniferous sedimentary succession of Rangit Gondwana Basin, Sikkim Lesser Himalaya (Figure 1). Fifteen samples from each (lower and upper) sequence of the Lower Gondwana Group in the Rangit basin

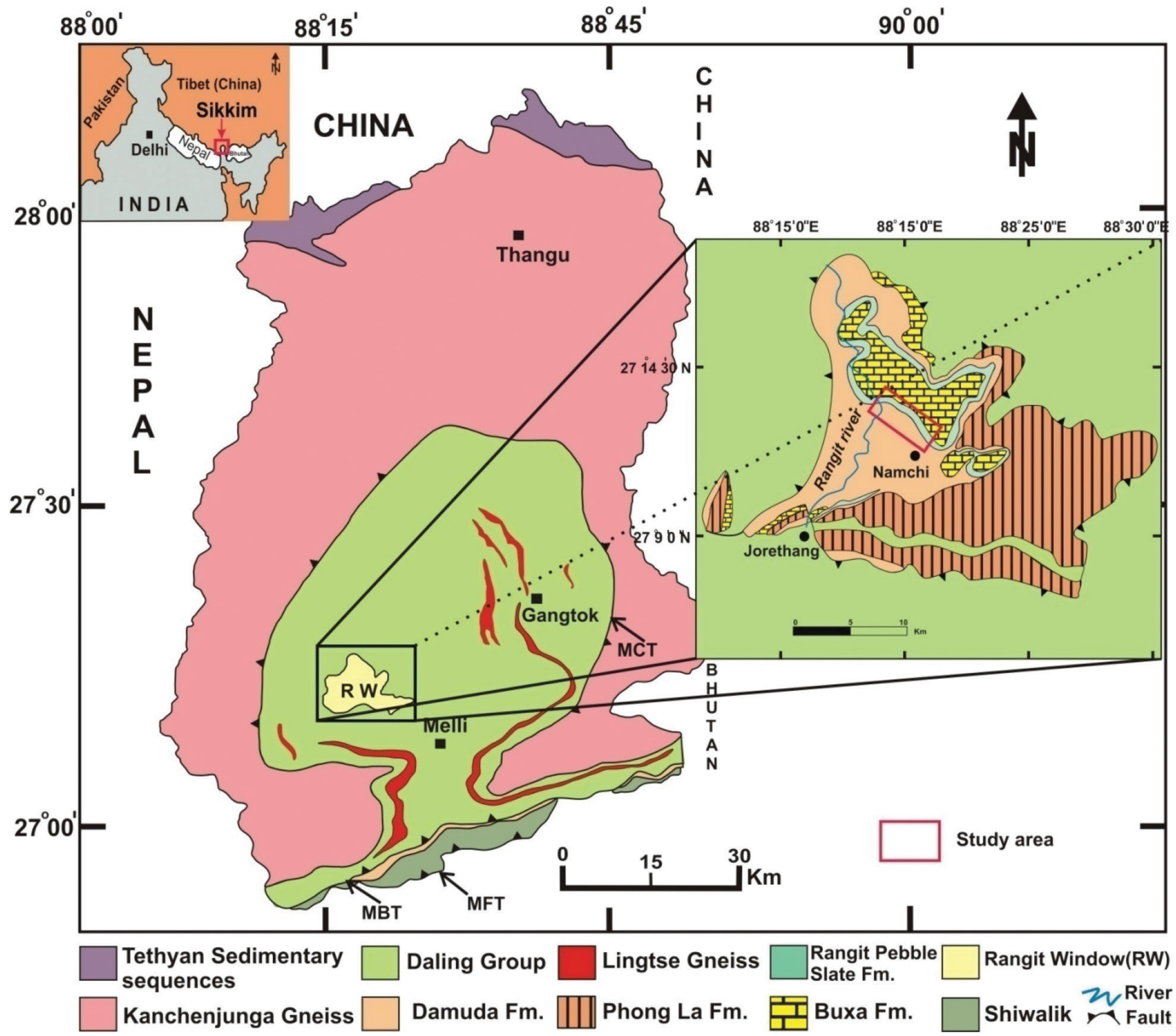

Figure 1: Geological map of Sikkim Himalaya and study area (after Ray and Neogi, 2011; GSI, 2012; Chakarborty et al., 2016; Priya et al., 2019).

were geochemically analyzed by X-Ray Fluorescence (PANalytical, Axios). Geochemical analyses of major oxide elements like SiO_2, Al_2O_3, TiO_2, MnO, MgO, K_2O and Na_2O present in sandstone and shale samples were performed at the geochemistry laboratory in Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow. All the standard procedures have been followed for sample preparation (Takahashi, 2015). Loss on Ignition (LOI) was quantitatively measured by weight difference after ignition at 1000°C.

Sequence Stratigraphy of the Study Area

Sikkim Lesser Himalaya is the amalgamation of Lithostratigraphic sequences of different ages between two recognized tectonic boundaries i.e. Main Boundary Thrust (MBT) and Main Central Thrust (MCT, Figure 1). Further, it can be divided into two sub-sections on the basis of different stratigraphic units i.e. Lower Lesser Himalaya and Upper Lesser Himalaya (Ghosh et al., 2016; GSI, 2012). The present study area falls under the Upper Lesser Himalaya, which comprises Meso to Neoproterozoic cherty, stromatolitic, microfossiliferous Buxa Formation and Gondwana Group of Formation (Schopf et al., 2008; Tewari, 2011; Raichaudhari, 2002; Priya et al., 2019). The discovery of cyanobacterial microfossils, stromatolite assemblages, and carbon isotope chemostratigraphy of the Buxa Formation dolomite firmly established a separate stratigraphic unit separating it from Gondwana Group (Figure 1) of Sikkim Lesser Himalaya with an unconformity (Tewari, 2011; Schopf et al., 2008, Rey and Neogi, 2011) mapped a new Formation i.e. Phong La Formation around Rangit window which is siliciclastic (carbonate free) in composition and has been assigned to be equivalent to the Buxa Formation as shown in Figure 1. The upper sequences of the Lower Gondwana Group consists of repeated alternate bands of sandstone, shale and coal seams (Figure 2a) with Glossopteris floral assemblages (Acharya and Ray, 1977; Raichaudhari, 2002; Priya et al., 2019). While the lower sequence of the Lower Gondwana Group is composed of boulder beds, massive diamictite, sandstone and olive green shales which are included under the Rangit Pebble Slate (RPS) formation (Figures 2 b, c and 3). The Rangit Pebble-Slate Formation in Sikkim Lesser Himalaya of Upper Carboniferous to Lower Permian age is equivalent to Talchir Boulder Beds of peninsular Gondwana master basin of India. Paleogeographically, it was once an integral part of the Eastern Gondwana (Priya et al., 2019).

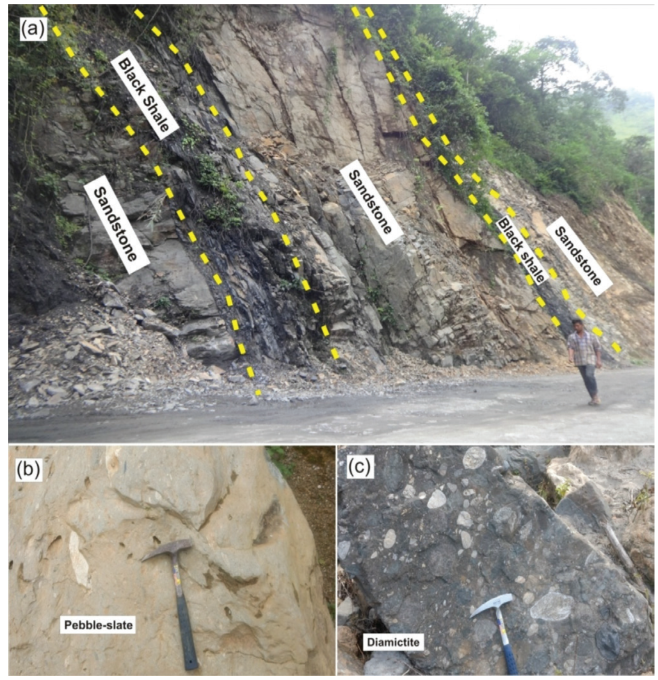

Figure 2: Field photograph (a) Repeated alternate bands of sandstone and shale of upper sequence of Lower Gondwana Group. (b, c) Pebble slate or/diamictite of lower sequences of Lower Gondwana Group from Rangit Gondwana Basin, Sikkim Lesser Himalaya well exposed between Tatapani and Jorethang along the road.

The presence of marine fossils like *Eurydesma* and glacial diamictite with large stromatolitic dolomite boulders and dropstone embedded in the coarser sandstone clearly indicates the influence of the glaciomarine environment (Acharya and Ray, 1977; Raichaudhari, 2002; Priya et al., 2019).

Siliciclastic Sediments Geochemistry and Provenance of Rangit Gondwana Basin

Geochemical analyses of sediments (major oxide elements) have been widely applied to interpret the provenance of sedimentary basin, tectonic setting and climatic condition in which they were deposited (Bhatia and Crook, 1986; Roser and Korsch, 1986; Suttner and Dutta, 1986). The concentrations of major oxides (wt.%) in sandstone, massive diamictite and shale are plotted along with the lithographic unit of upper and lower sedimentary sequences of Lower Gondwana Group of Rangit Gondwana Basin of Sikkim Lesser Himalaya (Figure 4). The sandstone and massive diamictite contain a high concentration of SiO_2 (74.53 - 91.32 %.) due to the dominance of quartz in it, whereas, black shale and olive green shale contain a low concentration of SiO_2 (21.45- 42.61 %) as given in Table 1 and Figure 4. Other major oxides such as Al_2O_3, Fe_2O_3, TiO_2, MnO,

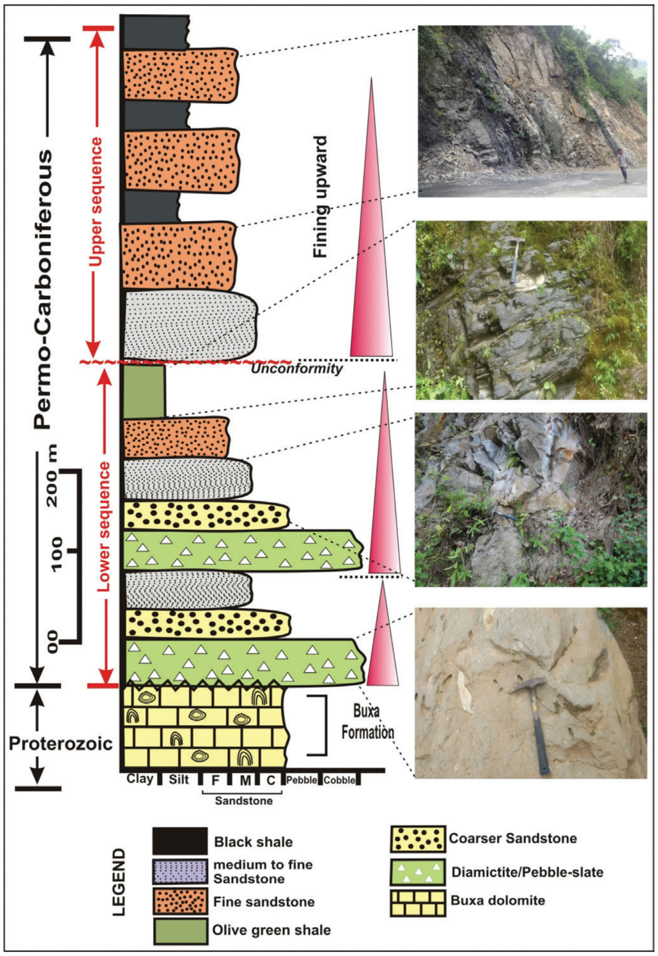

Figure 3: Lithostratigraphic succession of Buxa Formation, lower and upper sequences of Lower Gondwana Group well exposed in the Rangit Gondwana Basin (Rangit Window, Figure 1).

MgO, CaO, Na_2O, K_2O are also plotted (Figure 4) to depict the concentration of each element. The ratio of K_2O/Al_2O_3 is distinctly helpful to depict the content of clay and feldspar in the siliciclastic sample. The range of K_2O/Al_2O_3 ratio varies from 0.16 to 0.31 for clay minerals and 0.3 to 0.9 for feldspar (Cox and Lowe, 1995). In the present study, the siliciclastic sediments (massive diamictite and coarser sandstone) of the lower sequence have a higher value of K_2O/Al_2O_3 which ranges between 0.48 and 0.82 due to undecomposed feldspar grains. It implies that these sediments (lower sequence) were deposited under the cold environment. Whereas the sediments (rocks) of upper sequences contain more clay minerals that ranges from 0.16 to 0.31 due to consequences of intense weathering in a warm and humid climate. The low content of Na_2O in the upper sedimentary sequences of rocks also suggest its maturity and removal of alkali elements (K, Na) from the sediments.

Black shales of upper sedimentary sequences are characterised by the elevated concentrations of Al_2O_3, TiO_2, MgO, Na_2O, and K_2O as compared with olive green shale of lower sedimentary sequences (Figure 4). Compared to sandstones, the higher proportion of TiO_2 in the shales may be related to the existence of heavy minerals such as rutile and zircon in them.

Geochemical Proxies and Paleoclimatic Implication

Five important geochemical indexes have been used for determining the intensity of weathering and paleoclimatic condition of Lower Gondwana sedimentary sequences of Sikkim Lesser Himalaya. These geochemical indexes are: (a) Chemical Index of Alteration (CIA), (b) Index of Compositional Variation (ICV), (c) CaO + Na_2O + K_2O/Al_2O_3, (d) A-CN-K ternary/triangular plot and (e) SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) binary plot for detail investigation.

(a) **Chemical Index of Alteration (CIA):** It is one of the most important paleoclimate proxy-based on feldspar alteration during the geochemical weathering of sediments and provides access to calculate the intensity of weathering by following the equation given by Nesbitt and Young (1982),

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$$

where the major oxides of elements (Al_2O_3, Na_2O and K_2O) are expressed in molar proportion while the remaining content of CaO^* is incorporated into the silicate fraction of samples (McLennan, 1993). The CIA value has been widely applied for both glacial deposits (Condie et al., 2001; Scheffler et al., 2003; Dobrzinski et al., 2004) and non-glacial deposits (Aristizabal et al., 2005; Kahmann et al., 2008). The variation of CIA value from 45.26 to 70.33% with an average of 53.21% clearly signifies the dominance of unaltered feldspar due to weak weathering in a cold climate, whereas, the comparatively high values of CIA (62.53 to 86.68%) in the upper sequence of sandstone and shale indicated the intense weathering and warm humid climate (Table 1 and Figure 5a). The index value of the CIA is combined with alternate diamictite and sandstone facies to display and reconstruct the variation in the paleoclimatic conditions during sedimentation as shown in Figure 5a. Further, CIA values of Rangit Gondwana sediments (both upper and lower sequence) were compared with other CIA values of rocks and minerals for better understanding of geochemical behaviour of basin under different climatic environment condition (Figure 6).

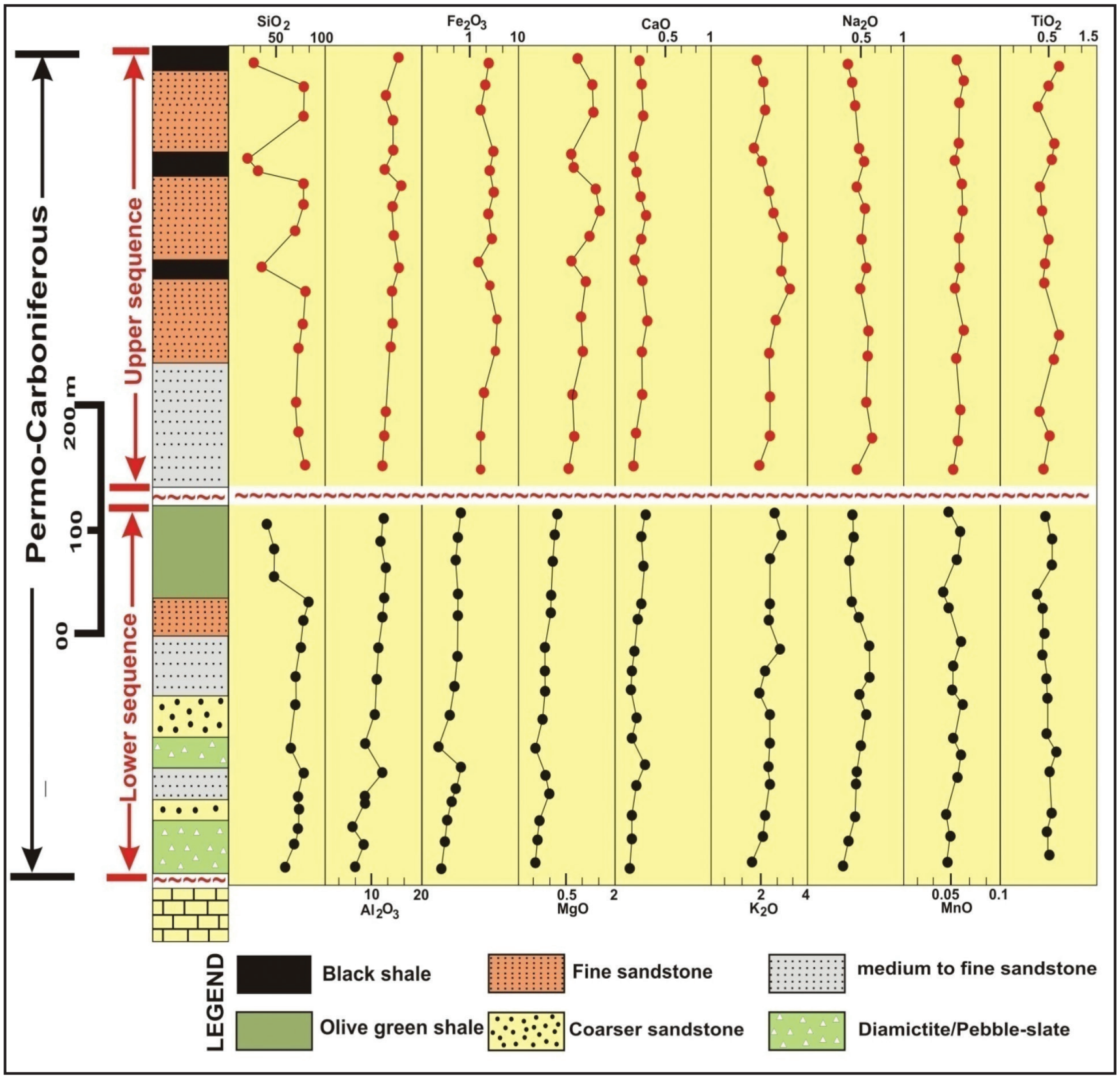

Figure 4: A plot of various elemental oxides for Rangit Gondwana sediments (upper and lower sequences) of Sikkim Lesser Himalaya.

The CIA values for Rangit Gondwana Basin ranges between 45.26 and 86.68% which is relatively the same values of granite to average shale and very close to Illite clay mineral of the other world basin (Nesbitt et al., 1996; Young, 2002). A plot between CIA and ICV (Figure 5c) gives a typical weathering trend indicating the shifting pattern of climate change through its maturity of sediments (Nesbitt and Young, 1984; Cox et al., 1995). A relationship between CIA and ICV suggests that lower sedimentary sequences of Lower Gondwana sediments are weak to moderately matured and have been less weathered due to cold climatic conditions whereas upper sedimentary sequences of Lower Gondwana sediments are highly mature and have shown intense weathering (Figure 5c).

(b) Index of Compositional Variation (ICV): The compositional maturity of sediments has been studied with the help of the Index of Compositional Variability (ICV) which is being calculated through an equation given by Cox and Lowe (1995) i.e.

$$ICV = (Fe_2O_3 + TiO_2 + MnO + MgO + CaO + Na_2O + K_2O)/Al_2O_3,$$

The different values of ICV infer the compositional maturity of the sediments. If the values of ICV is more than one, then sediment is considered to be compositionally immature which was deposited in the first cycle of deposition; whereas, if the values of ICV is less than one, then it is considered to be compositionally mature which get recycled and deposited in the stable

Table 1: Chemical composition (Major Oxide) of RPS Formation sediments (RGB 1-15, Lower sequence; RGB 16-30, Upper sequence) of Rangit Gondwana Basin, Sikkim, India

Sample	*RGB1*	*RGB2*	*RGB3*	*RGB4*	*RGB5*	*RGB6*	*RGB7*	*RGB8*	*RGB9*	*RGB10*	*RGB11*	*RGB12*	*RGB13*	*RGB14*	*RGB15*
SiO_2	81.79	76.18	85.27	86.81	82.61	77.67	85.09	83.07	85.09	79.48	78.62	85.53	63.04	48.67	69.84
Al_2O_3	4.32	5.65	4.64	4.01	8.21	8.12	4.49	6.81	7.06	8.26	9.01	7.06	14.11	16.25	12.09
TiO_2	0.11	1.33	1.23	0.09	1.19	2.91	0.31	0.27	1.29	2.11	0.27	0.25	2.83	4.78	1.75
Fe_2O_3	0.33	0.04	0.08	0.02	1.63	0.82	0.21	1.27	1.11	1.02	1.96	1.78	1.86	1.89	1.83
MnO	0.03	0.2	0.01	0.04	0.32	1.71	0.23	0.64	1.98	0.08	1.93	0.97	2.11	3.05	1.02
MgO	0.15	0.08	0.06	0.07	0.81	0.92	0.54	0.56	0.78	0.67	0.72	0.92	1.49	1.36	0.14
CaO	0.39	0.13	0.21	0.11	0.09	0.12	0.23	0.14	0.22	0.27	0.07	0.25	1.31	2.78	1.72
Na_2O	1.89	1.51	0.09	0.78	0.19	0.14	0.13	0.21	0.12	1.01	0.98	0.56	1.86	1.83	1.91
K_2O	2.13	3.41	3.82	3.96	4.03	2.66	2.85	3.83	2.56	3.11	3.07	2.31	3.01	2.88	3.67
P_2O_5	2.91	2.82	1.34	2.72	0.13	0.16	2.09	0.14	0.16	0.08	0.13	0.17	2.96	6.81	2.27
LOI	5.97	8.86	3.75	2.32	1.76	4.89	3.91	2.84	0.11	4.34	4.05	1.09	5.81	10.32	4.09
TOTAL	100.02	100.21	100.5	100.93	100.97	100.12	100.08	99.78	100.48	100.43	100.81	100.89	100.39	100.62	100.33
CIA	49.48	52.80	52.97	45.26	65.58	73.55	58.31	61.97	70.88	65.30	68.62	69.35	69.54	68.45	62.35
ICV	1.16	1.19	1.19	1.26	1.01	1.14	1.00	1.02	1.14	1.00	1.00	1.00	1.03	1.14	1.00
Sample	*RGB16*	*RGB17*	*RGB18*	*RGB19*	*RGB20*	*RGB21*	*RGB22*	*RGB23*	*RGB24*	*RGB25*	*RGB26*	*RGB27*	*RGB28*	*RGB29*	*RGB30*
SiO_2	87.21	78.09	77.87	84.07	84.21	82.61	76.18	91.09	83.07	84.09	80.48	80.02	83	83.04	71.67
Al_2O_3	7.01	12.42	15.35	9.04	7.96	8.21	11.12	5.02	7.81	8.06	9.26	9.94	8.86	9.11	14.25
TiO_2	0.32	0.25	0.11	0.23	0.09	0.19	1.21	0.31	0.27	1.09	0.11	1.27	2.15	0.33	3.78
Fe_2O_3	1.05	5.63	1.74	1.01	1.22	0.63	1.82	0.21	1.27	1.11	1.02	0.96	1.03	0.86	5.09
MnO	1.02	1.73	1.82	0.01	0.04	1.02	0.71	0.83	1.04	1.06	0.08	1.83	1.06	1.01	2.35
MgO	0.17	0.15	0.78	1.86	0.67	1.81	1.92	0.54	0.86	0.78	0.67	1.52	0.52	0.49	0.36
CaO	0.21	0.19	0.13	0.21	0.11	0.09	2.12	0.23	0.14	0.22	0.27	0.07	0.23	0.31	0.28
Na_2O	1.72	0.09	1.11	1.79	0.28	1.39	0.14	0.13	0.71	1.42	1.01	0.98	0.56	1.86	0.13
K_2O	1.63	2.13	1.41	1.22	3.88	3.03	2.66	1.75	3.83	2.36	3.11	3.07	2.31	3.01	1.78
P_2O_5	0.03	0.11	0.02	0.04	0.12	0.13	0.16	0.09	0.14	0.16	0.08	0.13	0.17	0.06	0.11
LOI	0.18	0.13	0.16	0.75	1.42	1.76	2.89	0.79	1.04	0.11	4.34	1.05	1.09	0.21	0.32
TOTAL	100.55	100.92	100.5	100.23	100	100.87	100.93	100.99	100.18	100.46	100.43	100.84	100.98	100.29	100.12
CIA	66.32	83.75	85.28	73.74	65.09	64.54	69.33	70.41	62.53	66.83	67.84	70.70	74.08	63.75	86.68
ICV	0.87	0.82	0.46	0.70	0.79	0.99	0.95	0.80	1.04	1.00	0.68	0.98	0.89	0.86	0.97

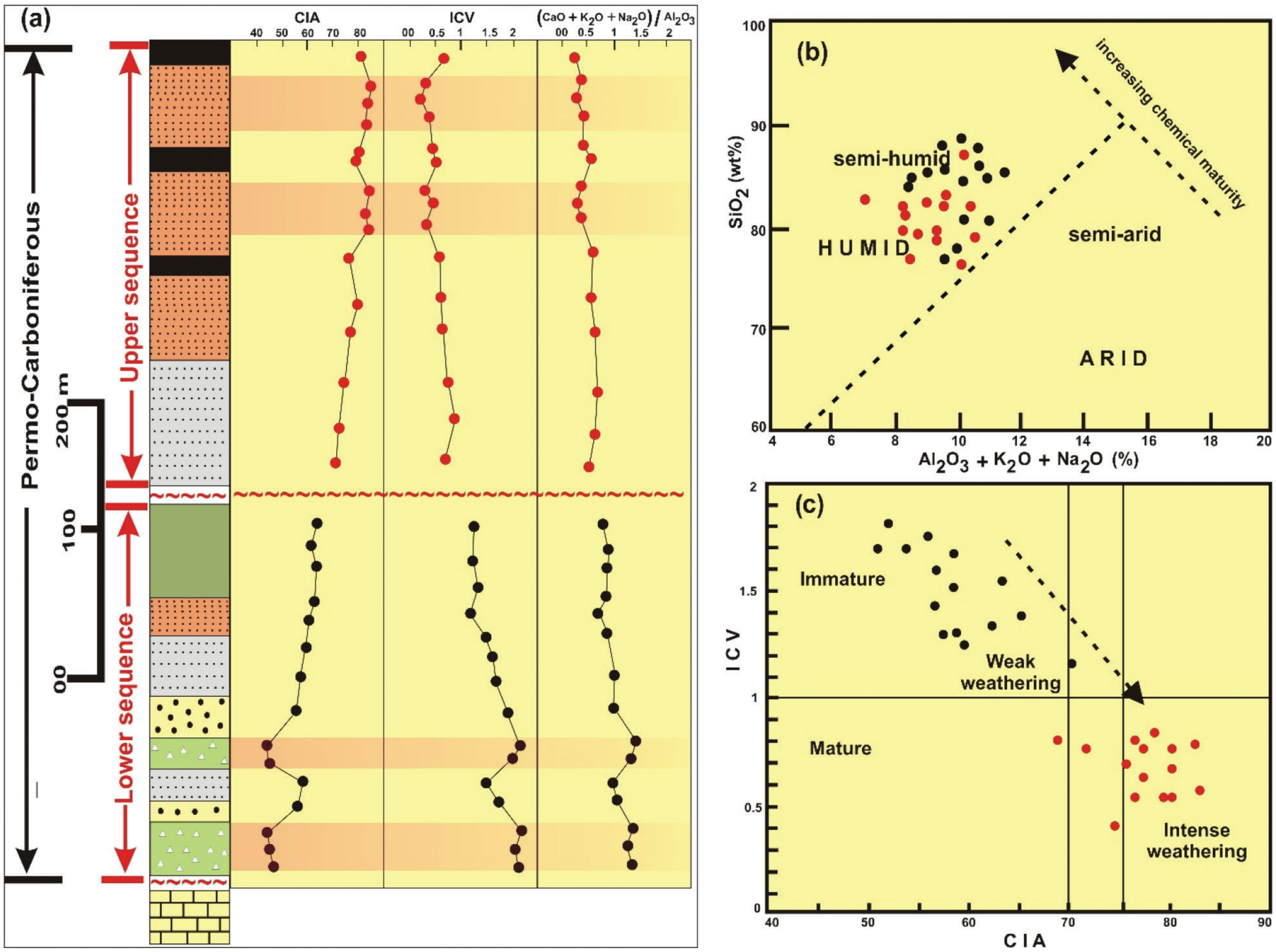

Figure 5: (a) The characteristics of geochemical proxies (CIA, ICV and CaO + Na_2O + K_2O/Al_2O_3) for the Rangit Gondwana sediments (b) SiO_2 versus (Al_2O_3 + K_2O + Na_2O) paleo-climate discrimination diagram for Rangit Gondwana sediments of Sikkim Lesser Himalaya (after Suttner and Dutta, 1986) (c)A binary plot between ICV and CIA showing the maturity and weathering condition for the Rangit Gondwana sediments (Nesbitt and Young, 1984; Cox et al., 1995).

tectonic environment (Cox and Lowe, 1995; Perri et al., 2012). Minerals such as feldspar, are being converted into aluminium (Al) rich clay minerals due to intense weathering of sediments and this progressive weathering trend decreases the values of ICV simultaneously (Potter et al., 2005). In the present study, the lower sedimentary sequences of the Lower Gondwana Group consists of mainly massive diamictite or/pebbly –slate and coarse sandstone and shows the high value of ICV (1.03 to 1.26), which inferred the compositionally immature sediments and have a low degree of weathering condition. The sandstone of upper sedimentary sequences show lower values of ICV (0.46 to 1.04) which indicate the compositionally mature sediments and a high degree of weathering condition (Figure 5a). Olive green shale of the lower sequence also indicates immature shale and a high percentage of non-clay silicate minerals with higher ICV values (1.14). While the black shale dominates aluminum bearing clay minerals with low ICV values (~ 0.6; Figure 5a).

(c) **CaO + Na_2O + K_2O/Al_2O_3:** The ratio of [(CaO+K_2O+Na_2O)/Al_2O_3] is another important geochemical indicator which has been used to portray different depositional environments during climate change. These elements (Ca, K, Na, Al) are more active and sensitive to hydro-geochemical changes and are affected during climate change (Zhang et al., 2008).

A mineral like aluminum silicate is mostly altered into different types of clay minerals (i.e. illite, montmorillonite and kaolinite) during chemical weathering. Thus, the value of [(CaO+K_2O+Na_2O)/ Al_2O_3] reflects the pattern of climate change during sedimentation into the basin. A higher value of [(CaO+K_2O+Na_2O)/Al_2O_3] for the lower sedimentary sequence (0.9 to 1.7) of the Lower Gondwana Group in the Rangit basin indicates the low degree of weathering in a cold climate. Whereas, a lower value (0.23 to 0.61) of upper sedimentary sequences strongly suggests intense weathering in warm humid climatic conditions (Figure 5a).

(d) A-CN-K ternary plot and (e) SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) binary plot:

The A-CN-K ternary plot and SiO_2 vs (Al_2O_3 + K_2O + Na_2O) binary plot have been used to depict the intensity of weathering and paleoclimate environment. Weathering trend and paleoclimate proxies provide clues to unravel the paleoclimatic condition of deposition (Suttner and Dutta, 1986; Nesbitt and Young, 1982). A ternary plot of A-CN-K (Al_2O_3 – CaO* + Na_2O – K_2O) given by Nesbitt and Young (1982) is applied to demonstrate the variable intensity of chemical weathering (Figure 7).

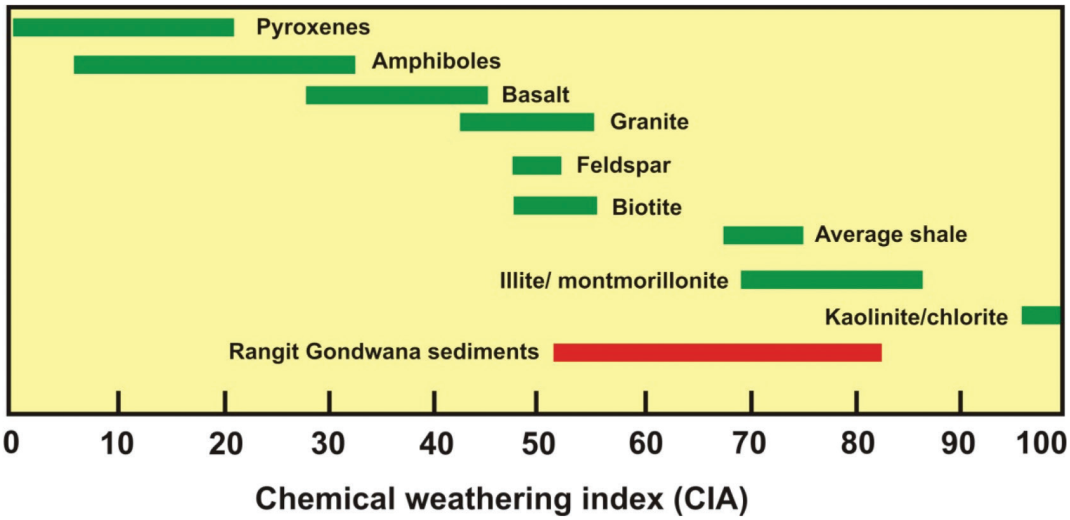

Figure 6: A comparison of CIA for Rangit Gondwana Basin sediments with CIAs for rock and minerals (Nesbitt et al., 1996 and Young, 2002).

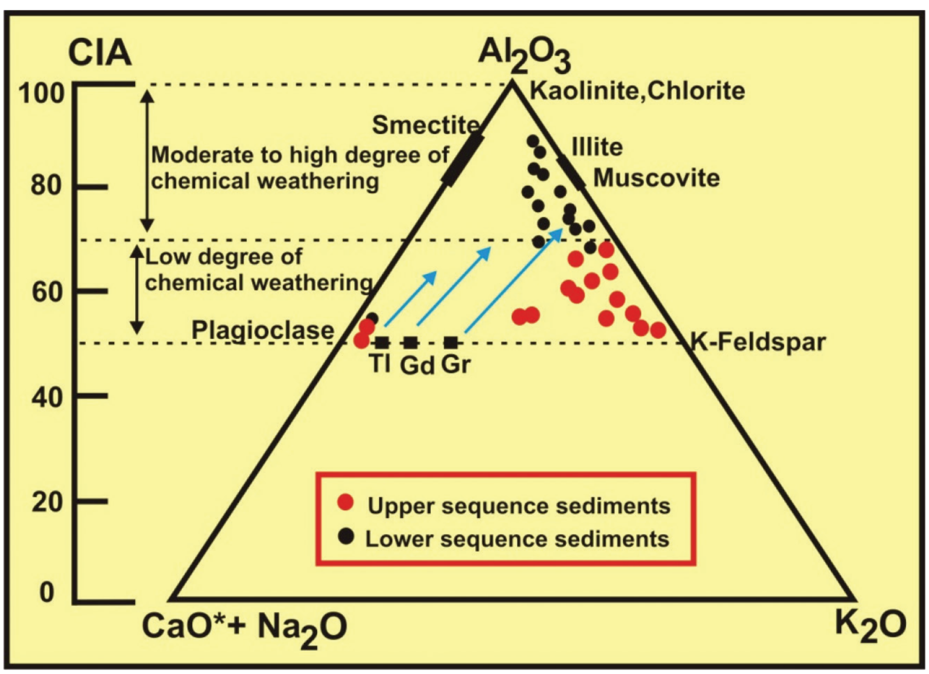

Figure 7: A-CN-K (Al_2O_3 - CaO* + Na_2O - K_2O) ternary plot of Permo-Carboniferous RPS sandstone and massive diamictite associated with Chemical Index of Alteration (CIA). Squares symbolize the average composition of Granite (Gr), Tonalite (Tl) and Granodiorite (Gd) with other minerals (after Nesbitt and Young, 1982).

The samples of lower sedimentary sequences of the Lower Gondwana Group in Rangit Basin are plotted close to K-feldspar mineral which suggests a low grade of weathering due to the cold glacial environment. Whereas the sediments of the upper sequences of the Lower Gondwana Group fall close to the $Al_2 O_3$ (A) end and along with the Illite mineral indicating the deprivation of K and Ca minerals from feldspar due to progressive weathering of meta-sedimentary and granite-like source rocks (Figure 7). Further, a plot between elemental oxides of SiO_2 and (Al_2O_3 + K_2O + Na_2O) also confirms warm and humid paleo-climate. The studied samples of lower sedimentary sequence fall in the area of semi-humid climatic conditions while the upper sedimentary sequence of Gondwana sediments occupied a humid area (Figure 5b). Therefore, both the A-CN-K ternary plot and SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) binary plot clearly suggest and indicate that the sediments of a lower sequence of Lower Gondwana Group of Rangit Gondwana Basin were deposited under a cold glacial environment whereas, the sediments of upper sedimentary sequences of Rangit Gondwana Basin were accumulated under warm and humid conditions.

Discussion and Conclusions

The sedimentary succession of the Rangit Gondwana Basin (upper and lower sedimentary sequences) of Lower Gondwana Group has been studied geochemically for the interpretations of climate change during the Permo-Carboniferous Period. The Gondwana Icehouse Period spanned between the Mid-Carboniferous and Early Permian waning by the early Late Permian in a high paleolatitude (Lopez-Gamundi, 2010). The lithological facies and sedimentological studies of lower sequences clearly indicate the influences of glacio-marine environment while the upper sedimentary sequences are the consequences of fluvial-deltaic sedimentation. The lithofacies of lower sequences indicate the development of transgressive system tract (fining upward sequence) due to glacioeustatic sea level rise and subsidence along basin margin (Gamundi, 2010; Priya et al., 2019). The upper litho-sequences with repeated alternate bands of sandstone, black shale and coal seams depict the fluvial and deltaic environment of deposition. The geochemical signatures in the form of major oxides have been interpreted with the help of various diagrams plotted based on the geochemistry of the sediments. The concentrations of major oxides have been plotted along with the lithostratigraphic column to show the variation in the concentration of various elements (Figure 4). The massive diamictite, coarser sandstone and fine sandstone are enriched with SiO_2 (Figure 4). The sediments of the upper sequence is enriched with Al_2O_3 indicating that sediments have gone through the intense weathering in the presence of warm and humid climate. Various plots i.e. Chemical Index of Alteration (CIA), Index of Compositional Variation (ICV), CaO + Na_2O + K_2O/Al_2O_3, A-CN-K ternary plot and SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) deciphered the climatic and weathering condition of both groups of litho-sequences (Figures 5 a-c, 6 and 7). Hence, the chemical composition and weathering pattern of both upper and lower sedimentary sequences of Rangit Gondwana sediments are characteristically different from each other due to variant paleo-climatic conditions. The lower sequences of Rangit Gondwana sediments of Sikkim Lesser Himalaya witnessed the cold (glacial) and semi-humid paleoenviornment conditions, whereas upper sequences of Rangit Gondwana sediments is influenced by warm and humid climatic condition (Figure 5a-b). The weathering trend also supports this paleoclimatic conditions with maturity and weathering pattern of sediments (Figures 5 a, c and 7). This wide variation of the depositional environment from cold to warm indicates the paleo-global climate change and allows us to reconstruct the paleogeography and paleoclimate that prevailed during the Permo-Carboniferous period, a major cryospheric or climate change on the earth. It will also help us to understand the Peri-Gondwana extension in the Tethyan realm of the Himalaya. Geochemical signatures of the Gondwana basin of Sikkim Lesser Himalaya indicate that lower and upper sequences of the Lower Gondwana Group are compositionally variable in terms of elemental concentration due to different environmental conditions. The lithofacies of the lower sequence of sediments witnessed the influence of both cryogenic and marine environment while the upper sequences are subjected to fluvial-deltaic and warm-humid climate. The enrichment of SiO_2, Al_2O_3, TiO_2, MnO, MgO, and K_2O indicates that these sediments were derived from felsic source areas which might be derived from high-grade metamorphic rocks and plutonic igneous rock. The Chemical Index of Alteration (CIA), Index of Compositional Variability (ICV), CaO + Na_2O + K_2O/Al_2O_3, and SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) values also suggest that the deposition of lower sedimentary sequences took place in the cold environment and upper sequences in warm humid condition. The A-CN-K ternary plots and CIA vs ICV binary plot indicate that the source area was subjected to prolonged intense chemical weathering from low to high grade due to shifting of cold to warm humid paleo-climatic condition. This paleoclimatic variation is also recorded from major Gondwana basins of the Western Gondwana (Africa and South America) and Eastern Gondwana (India, Antarctica and Australia; Histon et al., 2013).

Acknowledgement

The authors are thankful to the Head, Geology Department, Sikkim University for his constant support and providing all essential facilities to work in the field and laboratory. The authors are also sincerely thankful to the Director, Birbal Sahni Institute of Palaeosciences, Lucknow, India for providing a geochemical laboratory facility to analyze the samples.

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