IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 11, Issue 1 Ser. II (Jan. – Feb. 2023), 32-44
www.iosrjournals.org

A Comparative Statistical Study of the Geochemistry of Geothermal Fields in Peninsular and Extra-Peninsular India

Amitabha Roy

Ex-Senior Director, Geological Survey of India

Abstract

The present research is aimed at statistically analyzing two data sets drawn from two distinct geologic-tectonic regimes having two distinct geological and tectonic settings - one very tectonically active Alpine-Himalayan mountain chains of Extra-Peninsular and the other very stable landmass or Peninsular shield of India. The main thrust is to arrive at similarity or dissimilarity, if any, in their thermochemistry by applying the robust exploratory factor analysis. The results show that the thermal springs of Extra-Peninsular India are deep-seated hot acidic waters in contrast to shallower relatively less hot, with high pH alkaline waters of peninsular springs. The overall salt assemblage and concentration of F, Cl, SO4, Na, K, Mg, and Ca suggest the existence of hydrothermal system operating in geotherms of extra-Peninsular regime. In contrast in case of Penisular springstThe water is heated by convective circulation: groundwater percolating downward through fracture, failts reaching great depths of a kilometre or more where the temperature of rocks is high because the normal temperature gradient of the Earth's crust is about 30 °C (54 °F) per kilometre in the first 10 km. The geochemical characteristic as established by the exploratory Factor Analysis distinguishes non-volcanic/magmatic thermal sources as K-Na-HCO3 as against the magmatic Thermal Sources as Cl-HCO3-SO4-Na type of Extra- Peninsular springs, all suggestive of interactions of deep-seated magmatic fluids intermixing with meteoric water at shallow depth.

Date of Submission: 28-02-2023 Date of Acceptance: 11-03-2023

I. Introduction

In view of the ever increasing demand as well as the dwindling resources of conventional energy resources like coal, oil, gas, etc., an urgent need was felt all over the world for all forms of alternative renewable energy resources. This enthused a high interest in the exploration and exploitation of geothermal resources, which gained momentum. India was also not far behind in harnessing the geothermal energy.

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Table–1. Locations of Geothermal Springs of Peninsular and Extra-Peninsular

	Location	Geotherm_Field	Lat_Long
1	Agni kund	Bakreshwar	23.8833,87.3666
2	Suryakund	Bakreshwar	24.0900,85.4100
3	BakreshwarRiver	Bakreshwar	23.5200,87.2500
4	BakreshwarIB	Bakreshwar	23.5200,87.2500
5	Attri	Mahanadi_Graben	20.1230,85.3045
6	Tarabalo	Mahanadi_Graben	20.1605,85.1810
7	Athmalik	Mahanadi_Graben	20.4430,84.3010
8	Gopalpur	Mahanadi_Graben	19.2647,84.8620
9	Taptapani	Eastern_Ghat	19.2905,84.2350
10	Tatta	Damodar_Valley	23.4515,84.0212
11	Matang	Damodar_Valley	23.4920,84.2940
12	Sitakund	Damodar_Valley	25.2200,86.3600
13	Lachmikund	Damodar_Valley	25.0300,86.2900
14	Rajgir	Damodar_Valley	25.0100,85.2500
15	Tapoban	Damodar_Valley	24.5500,85.1900
16	Surajkund	Damodar_Valley	24.0900,85.4100
17	Takshing	Subansiri_Valley	28.2000,93.1500
18	Chetu	Subansiri_Valley	28.2500,93.2600
19	Naza	Subansiri_Valley	28.2730,93.2500
20	Jakrem	Meghalaya	25.5706,91.8708
21	Umjaraill	Meghalaya	25.4063,91.5355
22	Lingdem	Meghalaya	27.5332,88.4696
23	Yumthang	Meghalaya	27.7932, 88.7084
24	Raleng	Meghalaya	27.3502, 88.3228
25	Borang	NE_Himalaya	27.3657, 88.3277
26	Tatwani	Beas_Valley	32.0710,76.4310
27	Beas Kund	Beas_Valley	32.3821, 77.0838
28	Manikaran	Parbati_Vallet	32.0276, 77.3473
29	Chuza	Sutlez_Spiti	32.0345,78.3700
30	Jeori	Sutlez_Spiti	31.3140,77.4700
31	Napta	Sutlez_Spiti	31.3420,77.5820
32	Karchham	Sutlez_Spiti	31.3000,78.1050
33	Skiba	Sutlez_Spiti	31.3500,78.2230
34	Jamnotri	Tapoban	31.0000,78.2300
35	Banas	Tapoban	30.5720,78.2500
36	Chaudadani	Tapoban	30.5502,78.3336
37	Jhaya	Tapoban	30.5325,78.4012
38	Tunja	Tapoban	30.5325,78.4330
39	Gaurikund	Tapoban	30.3905,79.0135
40	Badrinath	Tapoban	30.4445,79.2930
41	Ghorshila	Tapoban	30.4158,79.3520
42	Kanakar	Tapoban	36.3250,79.3130
43	Juna	Tapoban	30.3600,79.4810
44	Tapoban	Tapoban	30.2930,79.373
45	Ungiya	Tapoban	30.0527,80.5313
46	Devkuna	Tapoban	29.5800,80.0856
47	Balati	Tapoban	30.0853,80.2023
48	Dobat	Tapoban	29.5150,80.3384
49	Panamik	Puga_valley	34.4650,77.3240
50	Pulthang	Puga_valley	34.4525,77.3330
51	Changlung	Puga_valley	34.5640,77.2825
52	Gul	Puga_valley	33.1620,75.0345
53	Yurdu	Puga_valley	33.4310,75.4430
54	Tatwain	Puga_valley	33.3030,75.5230
55	Galhar	Puga_valley	33.2040,76.5620
56	Puga	Puga_Valley	[illegible]
57	Chhumathang	Puga_valley	33.2200,78.2100
58	Sunsani	Beas_valley	32.4210,76.0425
59	Gajkhad	Beas_valley	32.0755,76.1050
60	Baijnath	Beas_valley	32.0710,76.4310
61	Sohnadh	Sohna	28.1500,77.0400
62	Sohna	Sohna	28.1500,77.0400
63	Didwaka	Toda	26.3530,76.1930
64	Rindi	Toda	27.0000,76.5300
65	Parai	Toda	24.1100,73.4110
66	Parsad	Toda	24.1300,73.4240
67	Gogbasp	Camby	21.4053,72.1544
68	Gogbatw	Camby	21.4053,72.1544
69	Dholera	Camby	22.1500,72.1200
70	Cambaywell	Camby	22.1400,72.4100
71	Barsan	Camby	23.2200,73.0500
72	Keedapad	Camby	23.2000,73.5600
73	Koknere	W.coast	19.4230,72.5100
74	Paduspada	W.coast	19.4105,72.5430
75	Akloli	W.coast	19.2930,73.0500
76	Vadavil	W.coast	18.0400,73.2700
77	Keed	W.coast	17.4300,73.2400
78	Toral	W.coast	17.1500,73.3500
79	Tapibasin	Satpura_Tapi	21.4196,76.1666
80	Tattapani	Tattapani	33.1435,74.2500
81	Bugga	Godavari_Valley	17.5500,80.4315
82	Gundala	Godavari_Valley	17.3830,80.5630
83	Manuguru	Godavari_Valley	17.5545,80.4425
	Pagdaru	Godavari_valley	17.5600,80.4300
84	Janampeta_spring	Godavari_Valley	18.0600,80.4000
85	Tatapani	Chhatisgarh	23.6993, 83.6842
86	Anhoni	Narmada_HotSpring	22.5960,78.6052
87	chhota anhoni	Narmada_HotSprings	22.6492,78.3546
88	Chavalpani	Narmada_HotSpring	22.8101,78.6426
89	Dhuni Pani	Narmada_HotSpring	22.6512,81.7519
90	Babeha	Narmada_HotSpring	22.7638,80.2760
91	Babeha	Narmada_HotSpring	22.7638,80.2760
92	Bendru Theertha	Karnataka	12.6805,75.1965

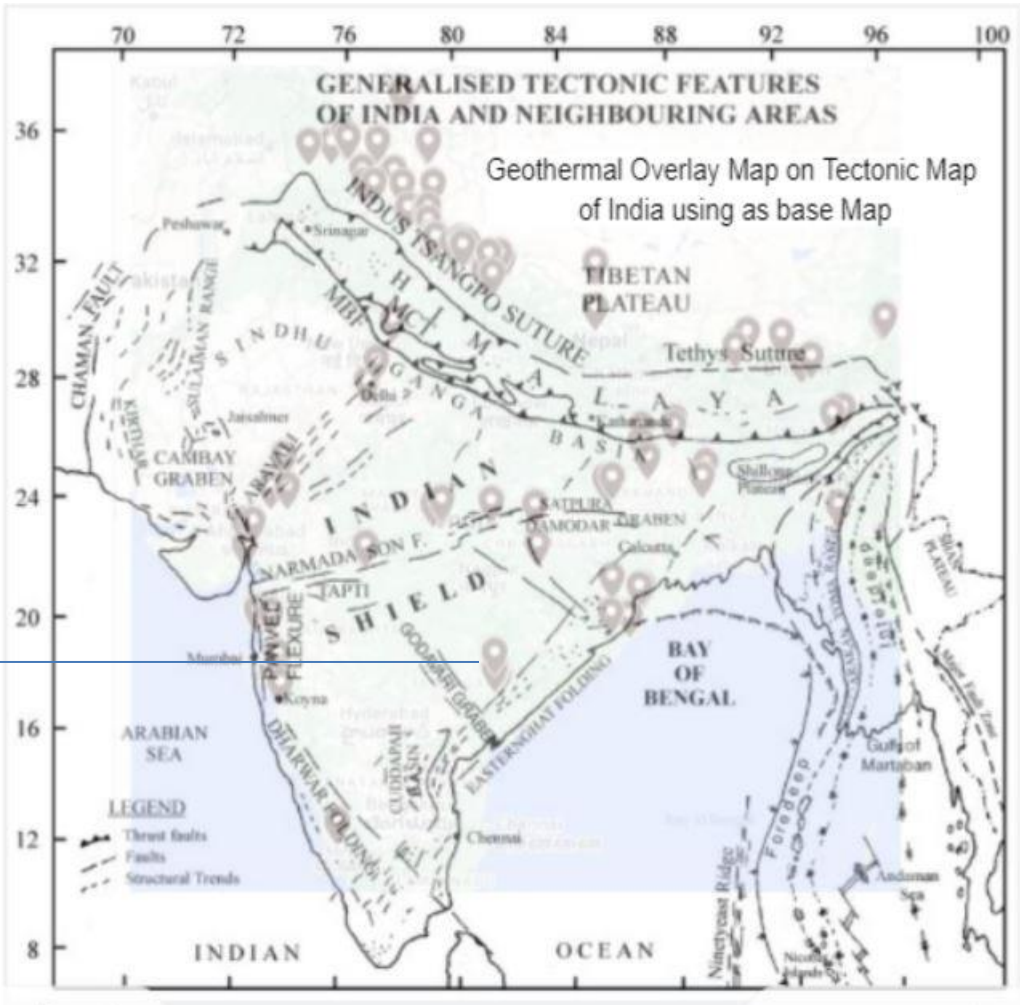


Fig. 1 Association of Geothermal Fields and Tectonic Settings

The surface manifestations of geothermal fields are the volcanoes, fumaroles, geysers, steaming grounds, and hot springs. There are about 340 hot springs spread over different parts of India, covering both the peninsular and extra-peninsular regions. The first attempt to list the hot springs in India was carried out by Schlagintweit in

1852, when he prepared an inventory of 99 thermal springs. Later, the government of India constituted a 'Hot Spring Committee' to examine the possibility of developing geothermal plants for power generation and other uses. In its 1968 report, the committee recommended that a systematic geothermal study and exploration be conducted in India in 1972.The GSI initiated geothermal exploration with the launch of the "Puga Project" in Jammu and Kashmir. In its search for hydrocarbons, , also collected significant geothermal data in sedimentary basins, both offshore' and 'on land, in the Peninsular region. The NGRI formed a 'Geothermic Group' for carrying out studies on 'heat flow values' in some parts of the country. The Central Electricity Authority (CEA) has associated itself with the UNDP geothermal project in India and with India in the Puga and Parvati projects for the utilisation of available geothermal resources for power generation. Mainly due to the ever increasing interest shown by various national agencies in geothermal energy, the growth rate of geothermal data has been constantly accumulated during the last few decades. The Geological Survey of India has brought out a special publication titled "Geothermal Atlas of India' (Ravi Shanker,1991) based on the data compiled from all sources of information, both published and unpublished, on geothermal activities in India. However, the lack of uniformity in data acquisition practices and data recording formats followed by different agencies and the manual handling of such huge quantities of data make the whole system of data storage, search, retrieval, and analysis laborious, cumbersome, and less efficient. This obviously neccessiated computerized system that offers both speed and storage capabilities. The GSI being the repository of most of the information concerning geological and other related data in the country, included in its field season 1993–94 program an R&D item No. 7/WB-5 (A. Roy, 1994). (CEA) associated themselves with the UNDP geothermal project inIndia and with India in the in the valley Puga and Parvati projects for utilisation of available geothermal resources for power generation.Mainly due to this ever increasing interest shown by various National agencies in geothermal energy, the growth rate of geothermal data has been constantly accumulated during the last few decades. The Geological Survey of India has brought out a special Publication titled'Geothermal Atlas of India' (1991) based on the data compiled from all sources of information both published and unpublished on geothermal activities in India. However, the lack of uniformity in data acquisition practices and data recording formats followed by different Agencies and also manual handling of such huge quantities of data make the whole system of data storage, searching retrieval and their analysis laborious, cumbersome and less efficient. This obviously neccessiated computerized system that offer both speed and storage capabilities.The GSI being the repository of most of the information concerning geological and other related data in the country, included in its field season 1993-94 program an R&D item No. 7/WB-5 (A.Roy,1994).

The geological regions of India broadly follow three physical features, and may be grouped into three regions: the Extra Penisular Himalayas and their associated group of mountains in the north, the Indo-Gangetic Plain in the middle; and the Peninsular Shield in the south. The peninsula is in the shape of a vast inverted triangle, bordered on the east by the Bay of Bengal and on the north by the Vindhya and Satpura ranges. The peninsular India comprises the Indian Shield, which is a geologically very old and stable part of the crust. exposed for long ages to denudation and approaching peneplanation. The Peninsula is mainly composed of Precambrian rocks and has Proterozoic and Phanerozoic cover. Along its coasts, there have been marine transgressions that have laid down sedimentary beds of the upper Gondwana, Cretaceous, and Tertiary ages. Major tectonic features/lineaments of Peninsular India include the West Coast areas of Maharashtra; the Son-Narmada-Tapi lineament zone at Salbardi, Satpura-Tapi areas in Maharashtra; Tattapani in Chhattisgarh, Rajgir-Monghyar in Bihar, Tatta and Jarom in Jharkhand, and the Eastern Ghat tracts of Orissa. 3. Rift and grabens of Gondwana basins of the Damodar, Godavari, and Mahanadi valleys The Extra-Peninsular India constitutes a part of the Alpine-Himalayan Tertiary Mountain Belt and is very active tectonically, falling within a severe seismic zone and being prone to earthquakes. The Extra-Peninsula is a region of folded and overthrust mountain chains, of geologically recent origin. The Extra-Peninsula is mainly composed of rocks from the Tertiary age.

Cause

A hot spring, hydrothermal spring, or geothermal spring is a spring produced by the emergence of geothermally heated groundwater onto the surface of the Earth. The groundwater is heated either by shallow bodies of magma or by circulation through faults to hot rock deep in the earth's crust by geothermal heat—heat from the earth's interior. In volcanic areas, water may come into contact with very hot rock heated by magma.

Geothermal fields are greatly correlated with the tectonic settings of a region. Their intimate association fits very well with the tectonic belts of India. The remarkable correlation between them has been observed when the two are superimposed upon each other. In the present study, all the geothermal springs were plotted onto the Google map by their GPS coordinates. Then this geothermal overlay map was superimposed onto the tectonic map of India, the latter serving as the base map.

Chemistry

Hot springs have an especially high mineral content, because heated water can hold more dissolved solids. This means a given hot spring can contain everything from calcium, magnesium, silica, lithium, and even radium. This means a given hot spring can contain everything from calcium, magnesium, silica, lithium, and even radium. The chemistry of hot springs ranges from acid sulfate springs with a pH as low as 0.8 to alkaline chloride springs saturated with silica and bicarbonate springs saturated with carbon dioxide and carbonate minerals. Some springs also contain abundant dissolved iron. Sulfur is an element that is frequently found in hot springs; it is dissolved in the springs through the surrounding rocks and soil. The most important microbial process that occurs in hot springs is the oxidation of sulfur, producing sulfuric acid. Hot springs stay clean either through a process of regularly replacing the water or by mixing in a chemical like chlorine, which kills bacteria and other pathogens by breaking down their chemical bonds.

Literature Review

Anirbid Sircar et.al. (2015) in their paper "Geothermal exploration in Gujarat: case study from Dholera", mainly from the point of view of exploration of geothermal energy for power generation, tried to unearth subsurface picture using geoscientific data, for example, Gravity survey, Landsat imagery, magnetotelluric (MT) survey, and water chemistry.According to them Hot springs exist over gravity high, which is the surface manifestation of deep and shallow water sources.

D Rouwet (2017), in his paper "Fluid Geochemistry and Volcanic Unrest: Dissolving the Haze ..." also subscribes the origin of hot springs to degassing of magma.

F. Tassi et al (2010) in his paper titled "Fluid geochemistry of hydrothermal systems…. (northern Chile)" based on chemical and isotopic composition, came out with four chemical facies of thermal discharges varying from Na–Cl - SO4 rich waters to Na-Ca–Cl−SO4, Ca–SO4−HCO3 and Ca–SO4, all suggestive of interactions of deep-seated magmatic fluids intermixing with meteoric water at shallow depth**.**

H. Baioumy (2015) in his paper titled "Geochemistry and geothermometry of non-volcanic hot …" subscribes to the view of degassing of magma.

Mohammad Noor et.al. (2021) in their paper "A geochemical comparison between volcanic and non-volcanic hot springs from East Malaysia: Implications for their origin and geothermometry" infer that t**he** geochemical characteristic distinguishes non-volcanic thermal sources as K-Na-HCO, while volcanic thermal sources present the Cl-HCO_3-SO_4-Na type.

At the backdrop of the cited literature in relevance to my research topic, I may say while the goal may be the same, the gaps in knowledge and unresolved problems that is lacking in their studies has been addressed in my research by adopting a definitive approach of statistical/mathematical model study giving an insight into arriving at distinguishing two suites of distinct geotherrns. The technique made comparison simpler and easier to follow between the fluid geochemistry inherent in the two distinctive geologic-tectonic environs - one very tectonically active Alpine-Himalayan Extra-Peninsular, and the other very stable landmass or Peninsular shield of India. There observed spectacular correlation between geothermal fields with tectonic zones with two very contrasting tectonic history with differing degree of severity - recent Himalayan thrust zones in Extra-Peninsula in the north as against the late Precambrian Proterozoic mobile belts in the Central Highland of Peninsular India..

Statistical Analysis of Multi-variate Geothermal Geochemistry

An attempt has been made in the present research to statistically analyze two data sets drawn from Peninsular and Extra-Peninsular regimes having two distinct geological and tectonic settings with a view to arriving at similarity or dissimilarity, if any, in their thermo-chemistry. Besides the basic descriptive statistical study, the main thrust is given here to the statistical analysis of two data sets, ideally representing two distinct geologic-tectonic environs, by applying the robust exploratory factor analysis. DATATAB statistics-calculator/factor-analysis software was employed for the present research study.

Data Set - 1 : Extra-Peninsular Geothermal Data.

NUM	TEMPC	pH	SPCMHO/cm	HCO3 mg/L	Cl mg/L	SO4 mg/L	TotHard	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	B mg/L	SiO2 mg/L	TDS mg/L
1	59	8.1	1271	300	163	62	0	14	5	210	13	12	5	80	800
2	96	7.7	827	170	133	36	131	44	15	88	19	0.8	33	60	514
3	59	7.1	5260	490	855	1244	1214	342	87	600	109	3.6	138	30	4072
4	24	8.2	795	210	102	83	136	30	15	110	19	1.2	25	25	488
5	56	7.6	1280	342	232	26	72	26	1	260	16	10	10	107	870
6	44	7.6	2015	303	200	340	302	103	11	260	45	6	13	87	1280
7	50	8.3	525	173	45	28	40	13	2	103	5	10	3	23	363
8	90	7.9	1045	276	170	33	0	52	12	135	27	3	10	83	874
9	73	7.5	410	145	30	55	0	38	13	30	7	1	3	50	378
10	52	7.8	25	15	2	0	12	3	1	1	0	0.2	0	2	20
11	50	8.2	700	248	72	48	40	13	2	140	6	5	3	65	480
12	55	7.7	400	272	10	14	0	56	24	8	5	0.4	0	68	366
13	54	7.6	845	445	35	0	0	50	52	50	10	1.2	0	41	536
14	55	6.8	2630	112	1485	22	230	70	13	490	37	1.6	19	115	1630
15	25	7.7	139	103	8	29	0	45	44	24	10	0.7	2	30	442
16	81	8.1	315	117	15	30	0	34	3	30	5	1.6	0	22	245
17	62	8	1460	861	48	14	72	14	99	290	43	3	5	91	1015
18	59	7.8	465	278	12	27	214	42	26	15	8	0.5	1	69	360
19	32	6.7	95	38	5	0	0	6	7	2	1	0.4	0	11	42
20	32	8.3	2000	953	86	0	0	0	47	80	83	0	0	18	0
21	68	6.4	1239	734	12	5	200	64	10	180	38	2	1	130	860
22	56	6.9	770	439	41	21	215	40	23	163	15	4	2	34	510
23	76	7.7	720	254	13	99	32	13	0	135	6	12.5	2.8	101	570
24	28	7.1	770	363	17	66	132	40	8	120	7	10	2	53	575
25	66	7.7	2030	1610	85	57	34	10	2	580	48	10	8	130	840
26	40	7.2	3641	259	11	1484	1352	504	22	200	6	2.5	1	35	2557
27	12	7	1060	233	58	383	536	169	28	10	2	0.2	0	18	834
28	12	7.1	63	32	3	0	24	9	0	2	0	0.4	0	6	42
29	68	6.9	386	112	30	72	40	14	1	56	4	6	1	35	235
30	9	8	178	0	6	12	52	15	3	9	3	1	0.9	9	114
31	18	8.3	205	0	7	2	88	27	5	6	2	0.2	0.9	9	123
32	34	7.4	2668	415	596	16	190	41	21	370	30	3	8	20	1399
33	40	7.6	469	264	13	10	186	44	18	19	10	0.3	0	28	279
34	35	6.6	446	49	104	6	20	7	1	75	3	7	1	28	260
35	52	7.2	8160	435	10	28	113	27	11	133	10	2.1	0	80	565
36	38	7.4	16630	362	154	370	396	127	19	150	17	1	0	60	1017
37	38	7.7	9800	353	35	36	158	54	5	86	9	0	0	40	638

Data Set- 2 : Peninsular Geothermal Data

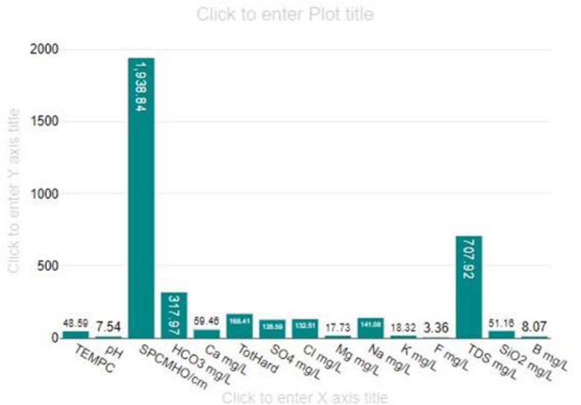
NUM	Temp_C	pH	SPCMHO/	HCO3 mg/	Cl mg/L	SO4 mg/L	TotHard	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	Bmg/L	SiO2 mg/l	TDS mg/L
1	32	7.5	5090	154	1375	210	872	204	88	660	18	0.7	0	18	2981
2	44	7.3	1115	339	165	24	270	82	16	110	6	0.4	0.9	46	500
3	40	7.7	1010	315	130	33	0	110	12	70	25	0	0	58	630
4	0	7.3	1410	390	195	75	0	65	40	210	5	0	0.1	40	830
5	26	7.8	1050	500	140	5	340	70	40	130	2	1	1.2	30	650
6	35.5	7.1	550	290	50	5	230	60	20	30	1	0.3	1.2	30	320
7	40	7.1	28980	190	1347	5	0	390	250	6810	55	0	0	16	0
8	0	7.2	960	410	110	25	0	45	15	95	2	0	0	4.5	0
9	43.5	7.4	8350	150	2725	10	0	105	40	1900	30	0.2	3	31	4790
10	99	0	0	1534	2428	672	0	9	8	1167	145	0	0	0	5744
11	40	7.4	4190	195	1485	0	0	90	40	875	14	0	0	25	0
12	39	7.6	550	183	71	33	160	40	21	40	2	0	0	22	328
13	54	7.5	13620	13	4800	185	4680	186	10	955	13	0	0.4	87	1614
14	43	9	2950	11	850	130	432	170	0.1	368	7	2	0.4	50	1868
15	64	8.6	4950	14	1210	144	890	348	0.2	391	8.5	7.2	0	65	2704
16	35	8.3	883	18	78	242	109	40	15	155	2	2.5	0	60	563
17	35	8	1917	71	426	107	100	32	6	292	4	1.5	1	5	965
18	61	7.6	1457	30	375	100	147	56	1.8	231	7.8	4	0.4	122	955
19	0	8	0	63	265	108	210	80	44	148	6	0.1	0	60	188
20	91	0	0	177	67	70	0	3	1	133	0	3	0.5	96	511
21	0	7.5	0	364	30	8	100	35	3	110	16	0.3	0	57	0
22	0	7.4	0	99	457	128	100	42	2	360	19	0.5	0	70	0
23	0	8	0	366	257	55	530	96	70	98	15	0.2	0	45	855
24	33	7.8	765	171	50	120.6	0	50	7.9	95	7.4	4	0	35	484.5
25	29	7.6	1077	128.6	166	182	0	20	13.4	208	4	5	0	28	756

Descriptive Basic Statistics (Upper:Extra-Peninsula,Lower:Peninsula)

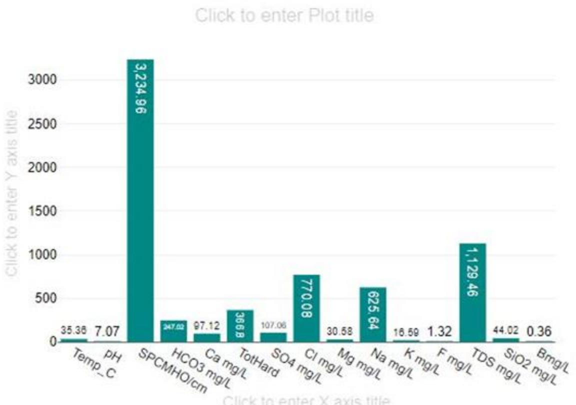
	TEMPC	pH	SPCMHO/cm	HCO3 mg/L	Ca mg/L	TotHard	SO4 mg/L	Cl mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	TDS mg/L	SiO2 mg/L	B mg/L
Mean	48.59	7.54	1,938.84	317.97	59.46	168.41	128.59	132.51	17.73	141.08	18.32	3.36	707.92	51.16	8.07
Std. Deviation	21.26	0.51	3,258.28	309.16	96.54	296.42	315.61	283.27	22.52	155.34	23.27	3.77	761.64	36.04	23.16
Minimum	9	6.4	25	0	0	0	0	2	0	1	0	0	0	2	0
Maximum	96	8.3	16,630	1,610	504	1,352	1,484	1,485	99	600	109	12.5	4,072	130	138

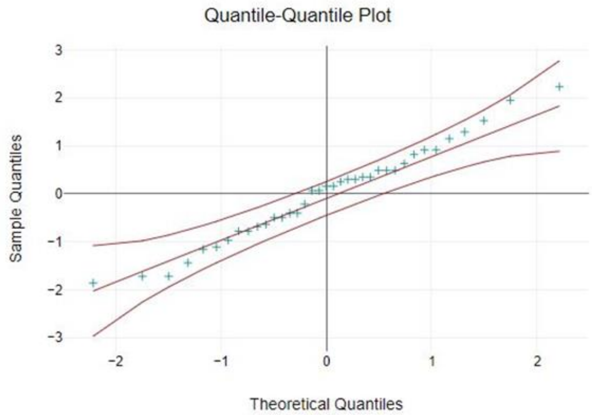
	Temp_C	pH	SPCMHO/cm	HCO3 mg/L	Ca mg/L	TotHard	SO4 mg/L	Cl mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	TDS mg/L	SiO2 mg/L	Bmg/L
Mean	35.36	7.07	3,234.96	247.02	97.12	366.8	107.06	770.08	30.58	625.64	16.59	1.32	1,129.46	44.02	0.36
Std. Deviation	26.53	2.17	6,209.25	303.73	96.64	933.93	137.52	1,126.61	50.93	1,361.05	29.3	1.93	1,476.2	29.52	0.68
Minimum	0	0	0	11	3	0	0	30	0.1	30	0	0	0	0	0
Maximum	99	9	28,980	1,534	390	4,680	672	4,800	250	6,810	145	7.2	5,744	122	3

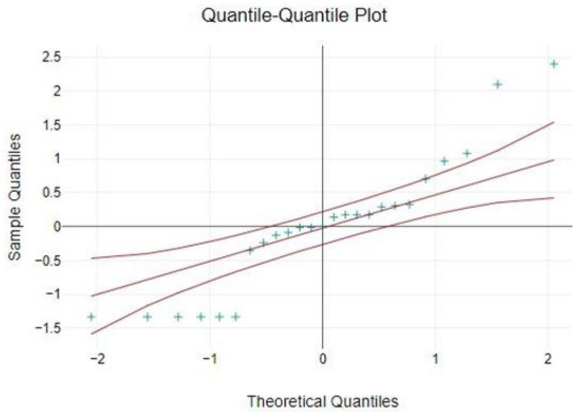
Extra-Peninsula Bar Chart



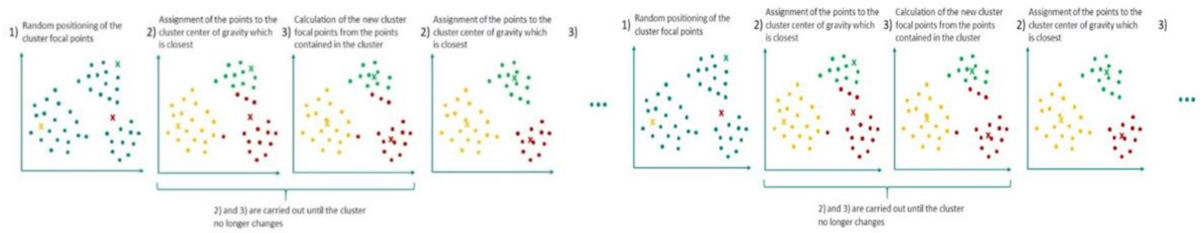
PeninsulaBar Chart







K-Mean Cluster

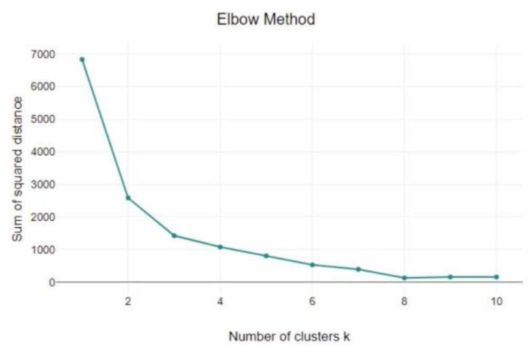


Interpreting the Results

Quantile-Quantile Plot : Purpose:Check If Two Data Sets Can Be Fit With the Same Distribution. The data sets are compared to the normal distribution, which forms the base distribution. Their quantiles are plotted along the X-axis as the theoretical quantile-quantile, while the sample quantiles are plotted along the Y-axis as sample quantiles. Now in the case of Data Set-1 (Extra-Peninsula), the points fall on the 45 degree reference line, which signifies that the data population is normally distributed. In the case of Data Set-2 (Peninsula), the data is distributed normally in the middle portion, but some points deviate on either ends of the reference line, signifying heterogeneity of the data due to a number of causes, like the heterogeneous character of the Peninsula both in lithological and tectonic settings. Moreover, some of the springs located in the Gangetic region may also contribute to this skewed pattern. Contrarily, the extra-Peninsular Himalyan region is a homogenous entity both in rock types and its arcuate tectonic settings, which are beautifully exhibited in the Q-Q plots.

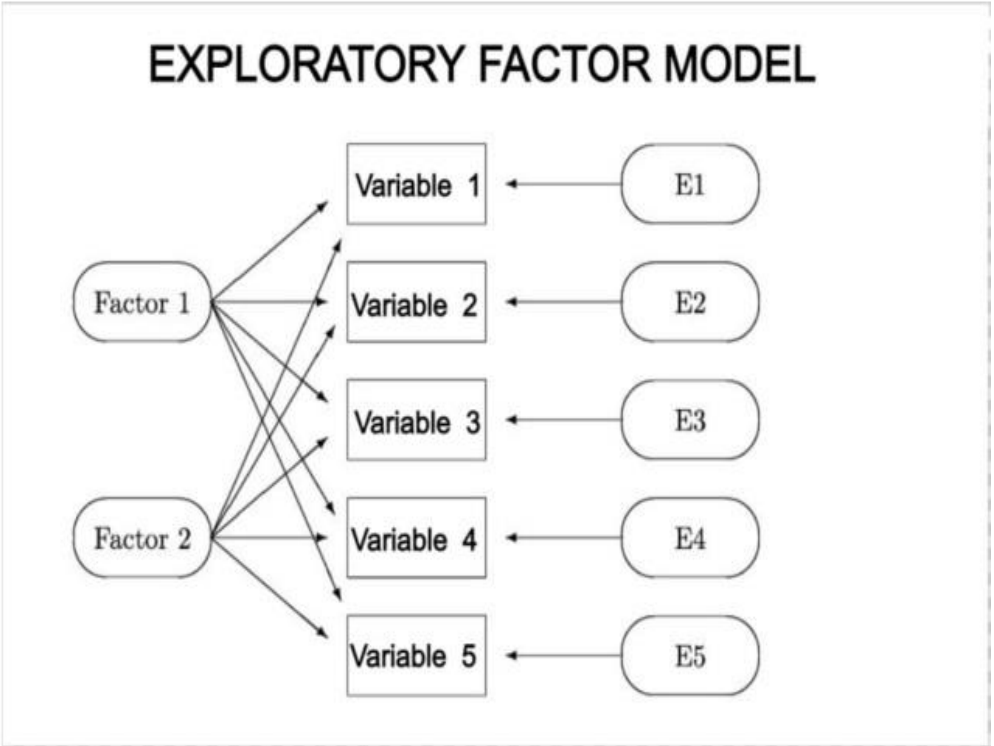
K-Means Clustering

Scaling data for k-means clustering : Since the variables under consideration do not have the same unit, the data has been first scaled before cluster analysis. The k-Means method, developed by MacQueen (1967), is one of the most widely used non-hierarchical methods. K-means clustering is a method of vector quantization, originally from signal processing, that aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean, serving as a prototype of the cluster. First, an initial partition with k clusters (given number of clusters) is created. Then, starting with the first object in the first cluster, Euclidean distances of all objects to all cluster foci are calculated. These steps are repeated until each object is located in a cluster with the smallest distance to its centroid (center of the cluster). When you want to calculate a cluster analysis, often the big question is how many clusters should I take. The optimal cluster number is determined by elbow Curve method.In the present study three clusters are taken based on Elbow curve.



Exploratory Factor Analysis

The exploratory factor analysis is a procedure that aims to uncover structures in large sets of variables. If you have a data set with many variables, it is possible to separate significant few, that is some of them correlatable with each other from insignificant many. The prime aim therefore is to reduce a large number of correlating variables to a few independent latent variables, the so-called factors. In other words the aim of the latent variables is to clarify as much of the variance of the original variables as possible.



Basic Concept of Factor Analysis and its significance in interpretation

$$\mathbf{X_j = \sum_{r=1}^{p} C_{jr}\, f_r}$$

where $\mathbf{f_r}$(r=1,2,3……..p) represents common underlying factors and C_{jr} indicates the factor loadings of variable X_j on factor f_r. Theoretical unkmown factors can then be expressed in terms of distinct groups of variables (in the present case fluid geochemical elements, which when correlated with the observed features of geothermal geochemistry of the area of investigation, provide significant insight into the causal factors (Roy. A., 1984).

To carry out this dimensional reduction of data, the following computational steps are necessary:

- Correlation Coefficient Matrix, the basis for factor analysis
- Unrotated Principal component Analysis
- Factor loading showing Variance explained by the variable on that particular factor matrix, Eigenvalues, Communality
- Detrmination of number of factors to retain
- Rotated (Varimax) Factor Analysis - Rotation method makes it more reliable to understand the output. There are a number of rotation methods available of which Varimax rotation method is used in the present study. Eigenvalues do not affect the rotation method, but the rotation method affects the Eigenvalues or percentage of variance extracted.

Correlation matrix - Extra-Peninsula

	TEMPC	pH	SPCMHO/cm	HCO3 mg/L	Cl mg/L	SO4 mg/L	TotHard	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	B mg/L	SiO2 mg/L	TDS mg/L
TEMPC	1	0.05	-0.06	0.22	0.09	-0.05	-0.1	-0.06	0.03	0.25	0.17	0.26	0.18	0.55	0.14
pH	0.05	1	-0.11	0.05	-0.25	-0.2	-0.3	-0.26	0.04	-0.16	-0	0.04	-0.1	-0.12	-0.25
SPCMHO/cm	-0.06	-0.11	1	0.19	0.17	0.31	0.34	0.3	0.11	0.25	0.19	-0.13	0.13	0.13	0.34
HCO3 mg/L	0.22	0.05	0.19	1	0	0.03	0.05	0.01	0.35	0.57	0.6	0.23	0.09	0.51	0.21
Cl mg/L	0.09	-0.25	0.17	0	1	0.22	0.31	0.23	0.21	0.7	0.51	0.01	0.54	0.24	0.6
SO4 mg/L	-0.05	-0.2	0.31	0.03	0.22	1	0.96	0.97	0.34	0.37	0.35	-0	0.55	-0.09	0.83
TotHard	-0.1	-0.3	0.34	0.05	0.31	0.96	1	0.97	0.37	0.41	0.37	-0.1	0.56	-0.08	0.85
Ca mg/L	-0.06	-0.26	0.3	0.01	0.23	0.97	0.97	1	0.34	0.32	0.28	-0.12	0.46	-0.07	0.81
Mg mg/L	0.03	0.04	0.11	0.35	0.21	0.34	0.37	0.34	1	0.3	0.6	-0.26	0.48	-0.02	0.49
Na mg/L	0.25	-0.16	0.25	0.57	0.7	0.37	0.41	0.32	0.3	1	0.71	0.38	0.58	0.53	0.75
K mg/L	0.17	-0	0.19	0.6	0.51	0.35	0.37	0.28	0.6	0.71	1	0.03	0.7	0.25	0.62
F mg/L	0.26	0.04	-0.13	0.23	0.01	-0	-0.1	-0.12	-0.26	0.38	0.03	1	0.03	0.44	0.11
B mg/L	0.18	-0.1	0.13	0.09	0.54	0.55	0.56	0.46	0.48	0.58	0.7	0.03	1	-0	0.76
SiO2 mg/L	0.55	-0.12	0.13	0.51	0.24	-0.09	-0.08	-0.07	-0.02	0.53	0.25	0.44	-0	1	0.21
TDS mg/L	0.14	-0.25	0.34	0.21	0.6	0.83	0.85	0.81	0.49	0.75	0.62	0.11	0.76	0.21	1

Correlation matrix - Peninsula

	Temp_C	pH	SPCMHO/cm	HCO3 mg/L	Cl mg/L	SO4 mg/L	TotHard	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	F mg/L	Bmg/L	SiO2 mg/L	TDS mg/L
Temp_C	1	-0.63	0.15	0.26	0.39	0.48	0.14	0.11	-0.13	0.15	0.45	0.33	0.15	0.17	0.53
pH	-0.63	1	0.1	-0.64	-0.14	-0.52	0.12	0.31	0.08	-0.07	-0.59	0.08	0.02	0	-0.36
SPCMHO/cm	0.15	0.1	1	-0.19	0.53	-0.13	0.33	0.78	0.8	0.93	0.22	-0.13	0.08	-0.1	0.06
HCO3 mg/L	0.26	-0.64	-0.19	1	0.1	0.59	-0.21	-0.28	-0.02	0.03	0.8	-0.34	-0.07	-0.44	0.46
Cl mg/L	0.39	-0.14	0.53	0.1	1	0.36	0.73	0.39	0.12	0.36	0.43	-0.18	0.24	0.02	0.59
SO4 mg/L	0.48	-0.52	-0.13	0.59	0.36	1	0.12	-0.12	-0.19	-0.04	0.73	0.13	-0.26	-0.13	0.65
TotHard	0.14	0.12	0.33	-0.21	0.73	0.12	1	0.32	-0.07	0	-0.07	-0.06	-0.01	0.31	0.13
Ca mg/L	0.11	0.31	0.78	-0.28	0.39	-0.12	0.32	1	0.62	0.65	0.08	0.15	-0.09	-0.01	0.14
Mg mg/L	-0.13	0.08	0.8	-0.02	0.12	-0.19	-0.07	0.62	1	0.87	0.22	-0.3	-0.07	-0.32	-0.09
Na mg/L	0.15	-0.07	0.93	0.03	0.36	-0.04	0	0.65	0.87	1	0.42	-0.19	0.06	-0.24	0.1
K mg/L	0.45	-0.59	0.22	0.8	0.43	0.73	-0.07	0.08	0.22	0.42	1	-0.25	-0.08	-0.33	0.65
F mg/L	0.33	0.08	-0.13	-0.34	-0.18	0.13	-0.06	0.15	-0.3	-0.19	-0.25	1	-0.13	0.35	0.06
Bmg/L	0.15	0.02	0.08	-0.07	0.24	-0.26	-0.01	-0.09	-0.07	0.06	-0.08	-0.13	1	-0.07	0.36
SiO2 mg/L	0.17	0	-0.1	-0.44	0.02	-0.13	0.31	-0.01	-0.32	-0.24	-0.33	0.35	-0.07	1	-0.2
TDS mg/L	0.53	-0.36	0.06	0.46	0.59	0.65	0.13	0.14	-0.09	0.1	0.65	0.06	0.36	-0.2	1

Extra-Peninsula

Explained Total Variance

Component	Total	% of variance	Accumulated %
1	5.74	38.26	38.26
2	2.74	18.24	56.5
3	1.49	9.94	66.45
4	1.18	7.84	74.29
5	1.07	7.15	81.44
6	0.83	5.55	86.99
7	0.78	5.17	92.16
8	0.43	2.9	95.06
9	0.34	2.28	97.34
10	0.19	1.27	98.61
11	0.13	0.84	99.45
12	0.04	0.25	99.7
13	0.02	0.15	99.85
14	0.02	0.13	99.98
15	0	0.02	100

Communality

	Extraction
TEMPC	0.39
pH	0.38
SPCMHO/cm	0.31
HCO3 mg/L	0.83
Cl mg/L	0.82
SO4 mg/L	0.94
TotHard	0.97
Ca mg/L	0.94
Mg mg/L	0.74
Na mg/L	0.88
K mg/L	0.88
F mg/L	0.56
B mg/L	0.77
SiO2 mg/L	0.79
TDS mg/L	0.97

Peninsula

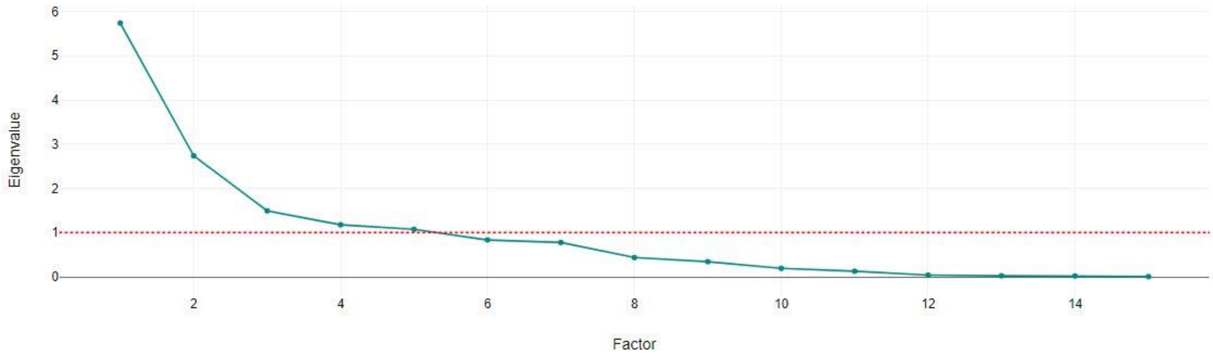
Explained Total Variance

Component	Total	% of variance	Accumulated %
1	4.29	28.6	28.6
2	3.61	24.09	52.7
3	2.29	15.27	67.97
4	1.44	9.63	77.6
5	1.21	8.08	85.68
6	0.93	6.2	91.88
7	0.39	2.61	94.49
8	0.27	1.82	96.3
9	0.17	1.16	97.47
10	0.17	1.14	98.61
11	0.12	0.78	99.38
12	0.05	0.36	99.75
13	0.02	0.14	99.89
14	0.02	0.1	99.99
15	0	0.01	100

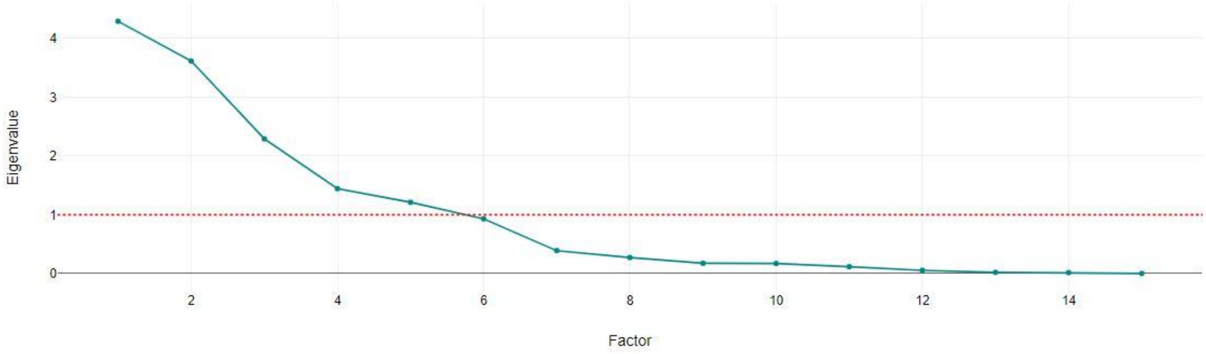
Communality

	Extraction
Temp_C	0.7
pH	0.64
SPCMHO/cm	0.96
HCO3 mg/L	0.87
Cl mg/L	0.92
SO4 mg/L	0.78
TotHard	0.67
Ca mg/L	0.81
Mg mg/L	0.92
Na mg/L	0.92
K mg/L	0.92
F mg/L	0.7
Bmg/L	0.49
SiO2 mg/L	0.6
TDS mg/L	0.74

Extra-Peninsula



PeninSula



Unrotated Component Matrix

Extra-Peninsula

	Component			
	1	2	3	4
TEMPC	-0.14	0.58	0.16	0.02
pH	0.26	0.14	-0.49	0.23
SPCMHO/cm	-0.38	-0.09	0.08	0.38
HCO3 mg/L	-0.35	0.62*	-0.28	0.49
Cl mg/L	-0.6*	0.19	0.05	-0.65*
SO4 mg/L	-0.8*	-0.45	0.19	0.23
TotHard	-0.83*	-0.46	0.18	0.16
Ca mg/L	-0.77*	-0.49	0.22	0.23
Mg mg/L	-0.56	-0.04	-0.65*	0.08
Na mg/L	-0.78*	0.51	0.07	-0.12
K mg/L	-0.74*	0.34	-0.45	-0.07
F mg/L	-0.06	0.56	0.48	0.08
B mg/L	-0.78*	-0.01	-0.19	-0.35
SiO2 mg/L	-0.24	0.78*	0.32	0.17
TDS mg/L	-0.97*	-0.06	0.11	-0.05

Peninsula

	Component			
	1	2	3	4
Temp_C	0.59	-0.29	0.45	-0.26
pH	-0.54	0.55	0.07	0.2
SPCMHO/cm	0.52	0.83*	0.04	-0.07
HCO3 mg/L	0.6*	-0.56	-0.44	0.04
Cl mg/L	0.69*	0.21	0.49	0.38
SO4 mg/L	0.64*	-0.55	0.14	-0.21
TotHard	0.21	0.26	0.68*	0.31
Ca mg/L	0.35	0.77*	0.21	-0.24
Mg mg/L	0.38	0.75*	-0.43	-0.17
Na mg/L	0.6*	0.69*	-0.24	-0.17
K mg/L	0.89*	-0.27	-0.24	-0.09
F mg/L	-0.2	-0.11	0.53	-0.6*
Bmg/L	0.09	0.04	0.13	0.68*
SiO2 mg/L	-0.31	-0.01	0.67*	-0.22
TDS mg/L	0.73*	-0.32	0.25	0.22

Rotated Component Matrix (Varimax)

Extra-Peninsula

	Component			
	1	2	3	4
TEMPC	0.15	0.57	-0.07	-0.18
pH	0.33	-0.11	-0.42	0.29
SPCMHO/cm	-0.46	0.2	-0.16	0.17
HCO3 mg/L	0.01	0.61*	-0.67*	0.12
Cl mg/L	-0.19	0.11	-0.05	-0.87*
SO4 mg/L	-0.96*	0.03	-0.09	-0.08
TotHard	-0.97*	-0	-0.09	-0.15
Ca mg/L	-0.97*	0	-0.04	-0.05
Mg mg/L	-0.29	-0.16	-0.77*	-0.19
Na mg/L	-0.3	0.59	-0.33	-0.58
K mg/L	-0.24	0.22	-0.73*	-0.48
F mg/L	0.1	0.7*	0.22	-0.08
B mg/L	-0.45	-0.01	-0.36	-0.66*
SiO2 mg/L	0.11	0.87*	-0.07	-0.14
TDS mg/L	-0.78*	0.24	-0.24	-0.48

Peninsula

	Component			
	1	2	3	4
Temp_C	0.61	0.09	0.36	-0.43
pH	-0.78*	0.15	0.01	0.08
SPCMHO/cm	-0.02	0.97*	0.12	0.03
HCO3 mg/L	0.84*	-0.16	-0.14	0.34
Cl mg/L	0.3	0.45	0.79*	0.07
SO4 mg/L	0.83*	-0.11	0.16	-0.21
TotHard	-0.14	0.25	0.75*	-0.15
Ca mg/L	-0.12	0.86*	0.11	-0.24
Mg mg/L	0	0.87*	-0.34	0.22
Na mg/L	0.18	0.93*	-0.13	0.12
K mg/L	0.91*	0.25	0.01	0.16
F mg/L	-0.06	-0.12	0	-0.83*
Bmg/L	-0.1	-0.04	0.52	0.46
SiO2 mg/L	-0.3	-0.16	0.3	-0.63*
TDS mg/L	0.68*	0.06	0.52	0.08

Interpreting the Results

Of the above computational steps, the most baffling issue is to determine the number of variables into a fewer number of factors i.e. to separate significant few from insignificant many.There are different criteria suggested by different researchers namely,

- Factors which have high eigenvalues
- The Eigenvalue > 1
- From the inflection point of scree or Elbow curve plot i.e. a graph of the eigenvalues (Y-axix) against the factors (X-axis) listed in the descending order.
- Communalities for each of the variables (somewhat like R^2 from Regresion analysis) at least 0.5

- The factor loadings for each variable should be ≥0.6 (Awang, 2014).

Factor analysis is a way to condense the data in many variables into a just a few variables. For this reason, it is also sometimes called “dimension reduction’. In the present study trial runs of PCA analysis taking into consideration of all the above criteria for determination of number of factors, came to a comprised conclusion that in the present study four factors which accounts for 75±2% of the total variance of the original variables “load”on a factor of Principal component is retained for rotation to avoid both overextraction and underextraction of factors that may have deleterious effects on the results.This also corroborates the criteria for communalities for each of the variable closer to one (0.9) and eigenvalue> 1

EXTRA-PENINSULA		PENINSULA	
Unrotated PCA	Rotated VARIMAX	Unrotated PCA	Rotated VARIMAX
F1 Cl-,SO4-,Ca-, Na-, K-,B-TDS-	F1 SO4, Ca, TDS	**F1** HCO3, Cl, SO4, Na, K, TDS	**F1** pH- , HCO3, SO4. K, TDS
F2 HCO3, SiO2	**F2** HCO3, F, SiO2	**F2** SPCMHO*,Ca, Mg, Na	**F2** SPCMHO*,Ca,Mg, Na
F3 Mg-	**F3** HCO3-, Mg-, K-	**F3** SiO2	**F3** Cl
F4 Cl -	**F4** Cl-, F-	**F4** B, F-	**F4** F-, SiO2-

SPCMHO/Cm* - is correctly defined as the electrical conductance of 1 cubic centimeter of a solution at 25 °C used to estimate the salinity , ionic strength and concentrations of major TDS solutes in natural waters.

From the above Factor analysis Table, following points of Fluid geochemistry emerge:

1.The thermal springs of Extra-Peninsular region are hot acidic in contrast to relatively cold high pH alkalinity of Peninsular springs.

2.The overall salt assemblage and concentration of F, Cl, SO4, Na, K, Mg, and Ca suggest the existence of hydrothermal system operating in geotherms of Extra-Pensulaa. In contrast,Peninsular springs are K-Na-bI-carbonate rich waters with low SO_4^- content and relatively higher contents of HCO_3 compared to other anions SO_4, Cl and F (Mohammad Noor, 2021).

3. Extra Peninsular sprngs are magmatic-hydrothermal manifestations, a phenomenon of magma progressively degassing in their decreasing order of solubility $CO_2 < SO_2 < HCl < HF$ i.e.“CO_2-first till HF-last” (Giggenbach 1987).

4.In case of the non-volcanic/magmatic thermal springs of Peninsular India, the water is heated by convective circulation: groundwater percolating downward through fracture, failts reaching great depths of a kilometre or more where the temperature of rocks is high because of the normal temperature gradient of the Earth’s crust—about 30 °C (54 °F) per kilometre in the first 10 km.

5. The geochemical characteristic as established by the exploratory Factor Analysis as tabulated above distinguishes non-magmatic thermal sources as K-Na-HCO_3 of Peninsular springs as against the magmatic thermal sources as Cl-HCO_3-SO_4-Na type of Extra-Peninsular springs..

6. Unlike Extra-Peninsular Himalayan region which is an extension of active tectonic Alpine-Himalayan main thrust zone with a homogeneous lithology, there is a heterogeneity both in lithological as well as multi-directional tectonic settings. Naturally, these distinctive geologic-tectonic environs have definite bearing on their fluid geochemistry.

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