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Ferrosyenites - an overview

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ABSTRACT
Through this paper we present an overview on the ferrosyenites. The ferrosyenites are very rare and geologically interesting rocks that are found in North America, Africa, Antarctica, China, Europe, Ukraine, Greenland and India. Mineralogically ferrosyenites are mainly composed of Fe-rich pyroxenes or Fe-rich olivine (fayalite), alkali feldspar minerals. 90% of ferrosyenites occur in association with gabbros in different alkaline complexes of the world, due to their petrogenetic relation. Chronologically ferrosyenites vary widely in age (9.1 ± 0.4 Ma to 1413 ±54 Ma). Along with the mineralogical and chronological diversity, the global distribution and nature of occurrence of the ferrosyenites is presented here.

Key words: Ferrosyenite, mineralogy, correlation, global distribution.

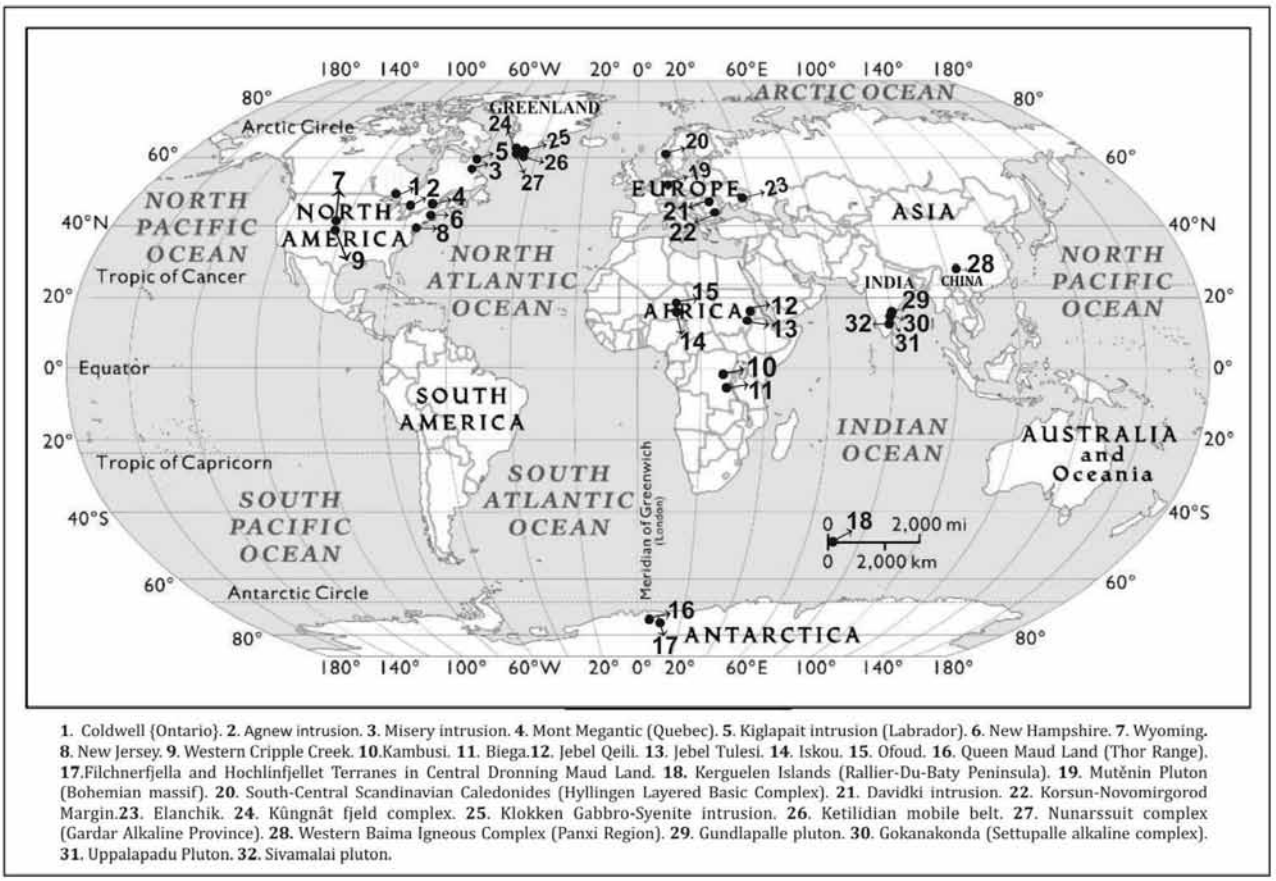
INTRODUCTION

Ferrosyenites are rare and geologically interesting rocks that are confined to specific geological setting; associated with the alkaline complexes. Worldwide, the ferrosyenites have restricted occurrence and are recorded at 32 places in North America, Africa, Antarctica, China, Europe, Greenland, India and Ukraine (Figure 1). The ferrosyenites are alkaline and subalkaline in character, which are mainly composed of Fe-rich pyroxenes or Fe-rich olivine (fayalite), alkali feldspars and amphiboles as essential minerals and quartz, biotite, titanite, zircon and calcite as accessory minerals. Globally, in majority of the alkaline complexes, ferrosyenites (~ 90 %) occur along with the gabbro plutons, rare exceptions are Gundlapalle and Sivamalai ferrosyenites of India. In Gundlapalle, the ferrosyenite is found in association with granite, close to the quartzite-limestone sequence of Palnad basin. Further, Gundlapalle ferrosyenite is unique due to the conspicuous presence of nontronite along with ferrohedenbergite. Presence of nontronite is an evidence for extensive hydrothermal alteration of ferrohedenbergite to nontronite, which is formed by the oxidation of Fe^{+2} to Fe^{+3} at the same time with the withdrawal of Ca (Eggleton, 1975). The nontronite is a rare secondary mineral which is identified by Madhavan et al., (1994) for the first time in Gundlapalle ferrosyenite of India. Nevertheless, apart from Gundlapalle other three ferrosyenites consist of ferrohedenbergite (New jersey-USA, Davidki-Ukraine, Klokken-Greenland) but with the absence of nontronite, which is missing due to the absence of hydrothermal fluids to alter the ferrohedenbergite to nontronite. The ferrosyenites vary widely in age (9.1 ± 0.4 Ma to 1413±54 Ma) and exhibit varying mineralogy and petrological characters in different plutons of the world (Table 1).

GLOBAL SCENARIO

On a global perspective, the ferrosyenites sign into proterozoic, as proved by the age determination of Kiglapait intrusion; Western Cripple Creek of North America, Nunarssuit complex from Gardar alkaline province of Greenland and Uppalapadu from peninsular India. Only couple of ferrosyenites represents palaeozoic period from Kambusi (South Africa) and China. The ferrosyenites from Kerguelen Islands of French territories represent Cenozoic period. The oldest ferrosyenite has been recorded at Kiglapait intrusion, which is located in the northern coast of the Labrador Peninsula, here the age of the syenite rocks is 1413±54 Ma old (De Paolo, 1981). The Nunarssuit complex is a very large massif, within the Gardar alkaline province in South Greenland that belong to Proterozoic age, the Rb-Sr age of pyroxene-fayalite syenite is 1154±14 Ma (Blaxland et al., 1978). The fayalite quartz syenite located at West Creek in the eastern part of the Pikes Peak batholith, Colorado has an age of 1085.6±2.5 Ma (Diane et al., 1999).

The ferrosyenite of Palaeozoic age is represented in Mutěnin pluton, which is a part of Bohemian massif (European Variscides, Germany). The pluton consists of "Lower carboniferous" ferrosyenite, which is exposed at north of the village St. Kramolin, (Zulauf et al., 2002). The Kambusi complex in Congo region, Africa is located about 30 km northwest of Bukavu. The complex consists of two intrusions, microgranite and microsyenite which are emplaced during the Cambrian (Ramvegri et al., 1985). The permian age was recorded at Baima igneous complex (BIC) which is located in the central portion of the Panxi rift in China, this complex consists of syenite, fayalite syenite, gabbro, precambrian rocks, granite and magnetite ore. The age of fayalite syenite is 252±2.5 Ma which is



1. Coldwell (Ontario). **2**. Agnew intrusion. **3**. Misery intrusion. **4**. Mont Megantic (Quebec). **5**. Kiglapait intrusion (Labrador). **6**. New Hampshire. **7**. Wyoming. **8**. New Jersey. **9**. Western Cripple Creek. **10**.Kambusi. **11**. Biega.**12**. Jebel Qeili. **13**. Jebel Tulesi. **14**. Iskou. **15**. Ofoud. **16**. Queen Maud Land (Thor Range). **17**.Filchnerfjella and Hochlinfjellet Terranes in Central Dronning Maud Land. **18.** Kerguelen Islands (Rallier-Du-Baty Peninsula). **19**. Mutěnin Pluton (Bohemian massif). **20**. South-Central Scandinavian Caledonides (Hyllingen Layered Basic Complex). **21**. Davidki intrusion. **22**. Korsun-Novomirgorod Margin.**23**. Elanchik. **24**. Küngnât fjeld complex. **25**. Klokken Gabbro-Syenite intrusion. **26**. Ketilidian mobile belt. **27**. Nunarssuit complex (Gardar Alkaline Province). **28.** Western Baima Igneous Complex (Panxi Region). **29**. Gundlapalle pluton. **30**. Gokanakonda (Settupalle alkaline complex). **31**. Uppalapadu Pluton. **32**. Sivamalai pluton.

Figure 1. Global distribution of ferrosyenites.

determined by SHRIMP zircon U–Pb technique (Gregory Shellnutt et al., 2008).

The youngest ferrosyenite of the world is located in Rallier du Baty ring complexes (South Centre) of Kerguelen archipelago of the southern Indian Ocean, which occupies an area of 6500 Km^2. The fayalite syenite here has recorded an age (K-Ar) of 9.1 ± 0.4 Ma (Dosso et al., 1979).

Tectonic Setting of the Ferrosyenites in the World

The ferrosyenites mostly occur in the rift, shear zones, deep fault and orogenic related tectonic setups in the world, which is evident in the famous alkaline plutons and some layered complexes in North America, Africa, Antarctica, China, Europe, Greenland, Ukraine and India Table.1. At present the information on the detailed tectonic settings of the few ferrosyenites of the world is available but the gap in the information with respect to the remaining need to be filled.

Mineralisation in Ferrosyenites

REE Mineralisation is found in only two plutons namely, Misery Syenite intrusion and Devil's Slide ring dike, New Hamphsire. The REE mineralisation in the form of fluorapatite has been reported in the ferrosyenite. The fluorapatite crystals were partly or completely replaced by britholite-(Ce), thereby enriching the rocks in the REEs from the Misery syenite located in north Quebec in Canadian Shield (Petrella, et al., 2014). The genesis of the ferrosyenite has been interpreted due to the process of fractional crystallization in the Misery syenite intrusion (Petrella, et al., 2014). Chevkinite, a titano-silicate of the cerium earths, occur as a well crystallized accessory mineral in fayalite-quartz syenite of the Devil's Slide ring dike just northwest of the village of Stark, New Hamphsire (Howard et al., 1956).

Ferrosyenites in India

Proterozoic syenites are widely reported in the Indian sub-continent (eg. Leelanandam, 1989; Madhavan et al., 1994; Madhavan et al., 1995; Srivastava and Chandra, 1995; Sesha Sai, 2013). However, only four ferrosyenite plutons occur in India, viz. Gundlapalle, Gokanakonda and Uppalapadu in the Cuddapah intrusive province of Eastern Dharwar Craton (EDC) and the ferrosyenites of Sivamalai of Tamilnadu. The oldest ferrosyenite has been

recorded with U-Pb Zircon age as 1352±2 Ma, in India from Uppalapadu pluton (Vijaya Kumar et al., 2007). The age of the other two ferrosyenites was not determined yet, but one of the pluton which is intruded into proterozoic Cuddapah basin i.e. Gundlapalle ferrosyenite (3 Km^2) is located at a distance of 12 Km from Piduguralla (Lime city) in the Guntur district of Andhra Pradesh. This pluton is situated in the northern part of the Cuddapah intrusive province (CIP). The ferrosyenite pluton has a sharp contact with unique lithological units such as granite (Dharwars), Panyam quartzites and Narji limestones representing Palnad sub-basin of Kurnool group (Madhavan et al., 1994).

The Gokanakonda ferrosyenites are emplaced with in the Settupalle alkaline complex. The subalkaline ferrosyenites (5 Km^2) are exposed at the southern marginal portion of the Settupalle alkaline complex. As per mineralogical criteria, the ferrosyenites can be differentiated into two types i) fayalite ± clinopyroxene syenite and ii) fayalite ± quartz syenite which are marked by the Gundlakamma River. The contact between fayalite ± clinopyroxene syenite and gabbro on the eastern side and the contact between fayalite ± quartz syenite and the gabbro on the western side and in the Northern side with hornblende syenite and in the southern side with granite gneiss are sharp (Leelanandam 1989; Srinivasan and Natarajan 1990). The ferrosyenite hosted in Uppalapadu pluton is mainly associated with nepheline syenite, hornblende syenite, ferrosyenite, anorthosite, olivine clinopyroxenite and olivine gabbronorite. The ferrosyenite has sharp contact with olivine gabbronorite on the eastern side and partly with hornblende syenite and biotite schist on the western side (Krishna Reddy et al., 1997). The Sivamalai pluton of Tamilnadu consists of ferrosyenite, perthite syenite, lueco syenite, biotite nepheline syenite, hornblende syenite**.** The ferrosyenite has sharp contact with perthite syenite and partly with biotite nepheline syenite on the western side (Holland, 1901; Bose, 1968.1971; Takashi Miyazaki et al., 1999).

Tectonically, the Gundlapalle pluton is very close to a deep seated fault which trends in NE-SW direction (Kaila and Tewari; 1982.Madhavan et al., 1994). Among the four plutons namely Elchuru, Purimetla, Uppalapadu and Settupalle, the presence of ferrosyenites is found only in Uppalapadu and Settupalle. These four plutons are conspicuously confined to an extremely narrow linear belt which is close to the known basement fracture zone, with which the major Bouguer gravity axis runs in close parallelism in a NNE-SSW direction. This belt lies approximately at the junction zone between two contrasting major rock formations and between two fold belts: such as the Dharwar (granite-greenstone) belt towards the west and the Eastern Ghat (gneiss-granulite) mobile belt towards the east (Leelanandam, 1989). The Sivamalai ferrosyenite pluton from Tamilnadu lies within the palghat-Cauvery shear zone (Holland, 1901; Bose, 1968.1971; Takashi Miyazaki et al., 1999).

Table:1. Global distribution of ferrosyenites.

Country	S.No	Location	Rock Type	Mineral Assemblage	Age	Associated Rocks	References
NORTH AMERICA	1	**COLDWELL {Ontario}** {48^0 47′N:$86^0$30′W}	Ferroaugite syenite	Ferroaugite, Fayalite, Ferroedenite-Hastingsite and Ferrorichterite.	NA	Gabbro, Nepheline Syenite, Biotite-Gabbro, Granite, Quartz-Syenite, Hybrid Syenite, Granite Gneisses, Ultrabasic Intrusive.	Roger et at.1977 Roger et at.1993
CANADA	2	**AGNEW INTRUSION (Southern Province in central Ontario)** {$81^0$50′N:$46^0$21′W}	Ferrosyenite	Phenocryst of albite, Alkali feldspar, Hedenbergite, Fayalite.	NA	Leucogabbro.	Vogel et al.1999
	3	**MISERY INTRUSION (Northern Quebec)**	Ferrosyenite	Fayalite, Hedenbergite, Ferropargasite and Annite.	NA	Coarse grained syenite, Fine grained syenite, Medium grained syenite, Porphyritic quartz syenite	Petrella et al. 2014
	4	**MONT MEGANTIC (QUEBEC)** $45^0$27′ N:$71^0$07′ W	Syenite	Fayalite, Aegirine augite, Perthite and Quartz	NA	Gabbro	Tomas Feininger, 2003 Bedard et al. 1987

Country	S.No	Location	Rock Type	Mineral Assemblage	Age	Associated Rocks	References
	5	**KIGLAPAIT INTRUSION (Labrador)** {57^0 00′ N:61^{0}30′W}	Ferrosyenite	Fayalite, Mesoperthite.	1413±54 My	Gabbro, Troctolite	Barmina et al. 2002 De Paolo 1981
	6	**NEW HAMPSHIRE** {43^{0}46′N:72^{0}00′W}	Fayalite quartz syenite	Fayalite, Hedenbergite, Quartz, Chevkinite, Hornblende, Plagioclase.	NA	Syenite	Howard et.al 1956
	7	**WYOMING** {41^{0}38′N:105^{0}40′W}	Ferrosyenite	Olivine(Fa_{87}), K-feldspars, Plagioclase, Augite, Ilmenite, Quartz, Titanite.	NA	Anorthosite, Hornblende Syenite, Gneisses, Sedimentary Rock	Kenneth et al., 1987 Dennis et al., 1969
	8	**NEW JERSEY**	Clinopyroxene quartz syenite	Ferrohedenbergite, Mesoperthite, Quartz, Fayalite, Plagioclase.	NA	Hornblende Granitic Gneiss	Davis and John C 1972
COLORADO	9	**WESTERN CREEK Pikes Peak batholith** (38^{0}44′N:105^{0}08′W)	Fayalite quartz syenite	Microperthitic Feldspar, Pyroxene, Fayalite, Olivine, Quartz. Magnetite.	1085.6 ± 2.5 Ma	Olivine Gabbro	Diane et al., 1999
AFRICA **CONGO**	10	**KAMBUSI** {2 ^{0}15′S:28^{0}38′E}	Microsyenite	Hedenbergite and Fayalite,Fluorite	Cambrian	Microgranite	Ramvegri et al., 1985
	11	**BIEGA** {2^{0}22′S:28 ^{0}40′E}	Fayalite syenite	NA	NA	Granites. Syenite	Boutakoff, 1956 Kampunzu et al., 1985 Lubala 1986
SUDAN	12	**JEBEL QEILI** {15^{0}31′N:33^{0}47′E}	Fayalite syenite	Fayalite. Ferro-Magnesian Minerals, Ferrohastingsite, Riebeckite, Biotite.	NA	Hastingsite syenite, Gabbro, Riebeckite quartz syenite Microgranophyre Precambrian schist, Rhyolite Lava, Biotite microgranite dykes.	Ahmed 1975
	13	**JEBEL TULESI** {11^{0}34′N:29^{0}14′E}	Syenite	Fayalite, Biotite, Diopsidic Pyroxene.	NA	Peralkaline granite	Curtits et al., 1985
NIGER	14	**ISKOU** {18^{0}04′N:8^{0}52′E}	Ferrosyenite	Ferroaugite, Fayalite, Perthite.	NA	Leucogabbro	Daniel et al., 1991
	15	**OFOUD** {18^0 49′N:8^0 43′E}	Ferrosyenite	Sodic amphibole, Ferrohastingsite, Biotite.	NA	Anorthosite	Daniel et al., 1991
ANTARCTICA	16	**QUEEN MAUD LAND (THOR RANGE)** {72^{0}55′S :5^{0}20′E}	Fayalite Quartz syenite	Alkali feldspars, Fayalite, Quartz.	NA	Alkali Granites, Charnockite.	Kurt bucher et al., 2006

Country	S.No	Location	Rock Type	Mineral Assemblage	Age	Associated Rocks	References
EAST AFRICA **ANTARCTICA OROGEN**	17	**FILCHNERFJELLA AND HOCHLINFJELLET TERRANES IN CENTRAL DRONNING MAUD LAND** {72^{0}00′S:05^{0}30′E}	Fayalite bearing syenite	Alkali feldspar, Fayalite, Pyroxenes.	NA	Granitic migmatites	Sotaro Baba et al., 2002
FRENCH SOUTHERN **ANTARCTIC LANDS** **EUROPE**	18	**KERGUELEN ISLANDS (RALLIER-DU-BATY PENINSULA)**	Fayalite syenite	NA	9.1± 0.4 My	Syenites, Granites and Micro gabbro	Dosso et al., 1979
EUROPEAN VARISCIDES, GERMANY.	19	**MUTĚNIN PLUTON (BOHEMIAN MASSIF)**	Ferrosyenite	K-feldspar, Prismatic Amphibole, Biotite, Plagioclase, Quartz, Orthite, Epidote. Fe-ti oxides.	Lower Carboni-ferous	Diorite, Quartz diorite. Mylonite.	Zulauf et al., 2002
NORWAY	20	**SOUTH-CENTRAL SCANDINAVIAN CALEDONIDES (Hyllingen Layered Basic Complex)**	Quartz bearing ferrosyenite	Alkali feldspar, Hedenbergite, Olivine Ferroedenite, Albite.	NA	Dunite /Troctolite, Olivine –Rich Unit, Syenitic Differentiates.	Richard et al., 1981 Henning et al., 1995
UKRAINE	21	**DAVIDKI** intrusion {51^{0}14′N:30^{0}30′E}	syenite	Pyroxenes, Titaniferous Ferrohedenbergite and Hedenbergite.	NA	Gabbro and Plagioclasite	Krivdik et al., 1986
	22	**KORSUN-NOVOMIRGOROD MARGIN** {48^{0}14′N:31^{0}17′E}	Fayalite hedenbergite syenite	Fayalite, Hedenbergite, Ferrohastingsite	NA	Rapakivi Granite, Monozosyenite, Gabbronorite, Labradoritite, Granite.	Krividik et al., 1988
	23	**ELANCHIK** {47^{0}28′N:38^{0}12′E}	Fayalite – hedenbergite syenite.	Alkali feldspar Fayalite, Hedenbergite.	NA	Hedenbergite-ferrohastingsite syenite. Leucocratic Granosyenite and Granite	Karamsin,1979 Krivdik et al., 1986
GREENLAND **(South Greenland)**	24	**KÛNGNÂT FJELD COMPLEX** (61^{0}13′N:48^{0}26′W)	Ferrosyenite	NA	NA	Olivine gabbro, Ferrosyenogabbro, Quartz syenite, Granitic rocks	Emeleus and Upton, 1976. Stephenson & Upton et al., 1982
	25	**KLOKKEN GABBRO-SYENITE INTRUSION** {60^{0}56′N:45^0 05′W}	Ferrosyenite	Alkali feldspar, Fayalite, Pyroxenes, Ferrohedenbergite.	NA	Late Biotite Syenite Gabbro, Unlaminated Syenite, Layered Syenite,	Blaxland, and Parsons, 1975 Parsons, I., 1979

Country	S.No	Location	Rock Type	Mineral Assemblage	Age	Associated Rocks	References
	26	**KETILIDIAN MOBILE BELT** {60^{0}30′N:45^{0}50′W}	Fayalite-orthopyroxene quartz syenite	Fayalite, Hastingsitic Hornblende, Alkali feldspar, Quartz.	NA	Mozonite, Biotite Granite. Syenite Quartzmonozonite / Quartzmonozonite Gabbro	Thomas Frisch et al., 1976.
	27	**NUNARSSUIT COMPLEX (Gardar alkaline province)** (60^{0}46′N:48^{0}00′W)	Pyroxene-fayalite syenite	Alkali Feldspar, Ferro-Salite/ Hedenbergite and Fayalite.	1154±14 Ma	Alkali Granite, Augite Syenite	Hodson 1993 Ferguson et al., 1963 Blaxland et al., 1978
ASIA CHINA	28	**WESTERN BAIMA IGNEOUS COMPLEX (PANXI REGION)** {102^{0}04′N:27^{0}04′W}	Fayalite syenite	Fayalite, Pyroxenes, Amphiboles, Alkali feldspars. Quartz, Biotite,	252 ± 2.5 Ma	Gabbro, Syenites. Granite,	Gregory Shellnutt et al., 2008
INDIA							
ANDHRA PRADESH	29	GUNDLAPALLE PLUTON (A.P) {16°24'N :79° 52' E}	Ferrosyenite	Ferrohedenbergite, Alkali feldspars, Hornblende, Nontronite, Quartz, Biotite, Rutile.	NA	Granites, Quartzite. Limestones	Madhavan et al., 1994
			i) Fayalite ± clinopyroxene syenite)	Alkali feldspars, Fayalite, Titanoaugite/	NA		
	30	GOKANAKONDA (Settupalle Alkaline Complex A.P) {15°52' N: 79° 52' E}		Ferroaugite, Ferrohastingsite, Quartz, Biotite.		Gabbro, Hornblende Syenite, granite gneiss Amphibolite, Quartz Syenites, Nepheline syenite, Mafic Rocks.	Leelanandam et al., 1989 Srinivasan et al., 1990
			ii) Fayalite ± quartz syenite.	Alkali feldspars, Fayalite, Quartz, Biotite.	NA		
	31	UPPALAPADU PLUTON (A.P) {15035′N :79047′E}	Ferrosyenite	Pyroxenes, Fayalite, Alkali feldspar, Amphiboles,	1352+2 Ma	Gabbronorite, Olivine clinopyroxenite, Hornblende Syenites, Nepheline Syenites, Anorthosites, Quartz Syenites, biotite schist.	Krishna Reddy et al., 1997
				Inverted pigeonite, garnet.			Vijaya Kumar et al., 2007 Bhattacharyya et al., 2014
TAMILNADU	32	SIVAMALAI {77032′E:11002′N}	Ferrosyenite	Ferroaugite, Fayalite Alkali feldspars,	NA	Perthite Syenite, Lueco Syenites,Biotite nepheline syenite, Hornblende syenite	Subba rao et al., 1994 Bose,1968 Bose,1971

CONCLUSION

The ferrosyenites are very rare rocks which have distinct mineralogy and petrogenetic significance. Considering the mineralogical criteria, ferrosyenites are plutonic igneous rocks that have fayalite or Fe-rich pyroxenes as essential minerals. However, different authors from around the world used different nomenclature for these rocks. Most of the ferrosyenites from different parts of the world are associated with gabbroic rocks as these rocks have genetic relationship and are derived from gabbroic magma, but in some places the ferrosyenites are also found devoid of gabbroic association i.e. the Gundlapalle and Sivamalai ferrosyenites plutons in India. The age of ferrosyenites in the world is recorded to be from Proterozoic to Cenozoic period. The ferrosyenites of Uppalapadu area in EDC, India, is of Proterozoic age and is the second oldest body in the World after Kiglapait ferrosyenite. Through this work an attempt is made to compile the available data on ferrosyenites in the world with an objective to present an overview and also to indicate the gap. Further research on these rocks in the field of isotope geochemistry and geochronology will contribute to enhance the existing understanding of these rocks.

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Compliance with Ethical Standards:

The authors declare that they have no conflict of interest and adhere to copyright norms.

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