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Field Observations, Structural Analysis and Petrographic Study of Dolerite Dykes in Cacra, North Goa, India

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Abstract

This study examines the mafic dyke swarm exposed along the Cacra coast, North Goa, to interpret its structural orientation, petrography, and magmatic evolution. Field mapping and geophysical data reveal nine doleritic dykes trending ENE–WSW, NW–SE, N–S, and NNW–SSE, with CD-1 confirmed as N–S oriented. Although dyke host contacts are obscured, adjacent metagreywacke exposures likely represent the country rock. Petrographic analysis indicates medium- to coarse-grained dolerite comprising plagioclase, clinopyroxene, opaques, and alteration minerals such as chlorite, biotite, and iddingsite. Textures including porphyritic, sub-ophitic, and symplectic intergrowths with zoned plagioclase suggest a two-stage crystallization slow cooling at depth followed by rapid quenching. These features collectively indicate emplacement under dynamic magmatic conditions governed by pre-existing fractures within the Proterozoic basement of the Dharwar Craton.

Keywords: Dykes, Dolerite, Petrographic Analysis, Geophysical Survey

Introduction

The dyke swarms in Goa are predominantly doleritic and basaltic, and they display a range of trends, with some exhibiting significant local variations. These swarms are best exposed along the coastal regions of Goa, particularly at Aguada, Baga, Vagator-Chapora, and Arambol-Keri headlands. The dyke swarm is especially prominent in the talukas of Bardez and Pernem, where dykes cut through the Proterozoic basement rocks, including argillites, metagreywackes, and quartzites, belonging to the Sanvordem Formation of the Goa Group (Gokul, 1985; Fernandes, 2009; Dessai, 2018; Gadgil *et al.,* 2019). The Goa dyke swarm contains around 60 individual dykes, some of which represent multiple magmatic injections.

The present study investigates the dolerite dykes of the Cacra region, North Goa, focusing on their field characteristics, structural features, and petrographic attributes. Detailed petrographic analysis aims to elucidate the emplacement history, mineralogical composition, and tectonic significance of these dykes, with comparisons to other coastal dyke swarms along North Goa. Mafic and ultramafic dykes across the western coast and cratonic regions of India, including Goa, record major magmatic episodes related to the Mesozoic rifting of western India (Ashutosh *et al.*, 2025; Salve *et al.*, 2024; Patel *et al.*, 2020; Dongre *et al.*, 2017). Halls *et al.* (1982) reported an age of 2367 ± 0.1 Ma for an E–W trending diabase dyke, indicating widespread early Proterozoic dyke activity across the Dharwar Craton. This study contributes to the growing body of literature on dyke swarms in India and aims to provide valuable insights into the geological history of the region.

Geological Setting

The geology of Goa is dominated by Archean to Proterozoic rocks of the Dharwar Supergroup. Gokul *et al.* (1985) classified the Goa Group into four formations such as Barcem, Sanvordem, Bicholim, and Vagheri. Later revised by Dessai (2018) into two groups, the Barcem and Ponda, separated by an unconformity. Goa hosts mafic intrusions forming part of the supracrustal assemblage, including peridotite gabbro complexes, gabbroic intrusions, and mafic dykes (Dessai, 2018). These intrusions, younger than the metasediments, show minimal deformation (Dessai, 2011, 2018). The older intrusions peridotites, epidiorites, and metagabbros or metadolerites are Proterozoic, while younger dykes related to Deccan Trap volcanism show komatiitic to tholeiitic chemistry. The sequence begins with peridotites, followed by epidiorites, metadolerites, and tholeiitic dykes. Peridotites trend ENE–WSW and show low greenschist facies metamorphism; epidiorites trend NNW–SSE to N–S and are often altered to clay in mining zones; metadolerites trend NNW–SSE to NNE–SSW. Coastal dolerite dykes between Aguada and Palolem trend WNW–ESE to

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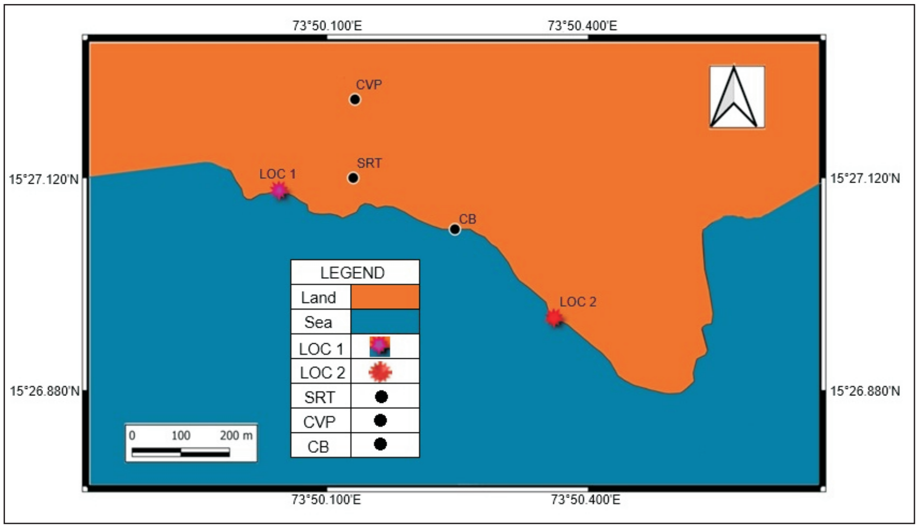

Fig.1. Location Map of Study area; Two locations of dykes are marked along with landmarks. (Blue color indicates sea and orange color demarcates land; Loc 1 - Location 1; CVP - Cacra View Point; Loc-2 - Location 2; CB - Cacra Beach; SRT - Sateri Ravalnat Temple)

ENE–WSW (Dessai, 2018). Dykes dated at 62.8 Ma (Widdowson *et al.,* 2000; Patil and Rao, 2002) correlate with early Deccan magmatism. Structural features and jointing suggest emplacement along preexisting fractures under contemporaneous stress fields (Deshmukh *et al.*, 2023; Gadgil *et al.*, 2019).

Study Area

The study area lies along the Cacra coast in Tiswadi taluka, North Goa, within the Sanvordem Formation of the Ponda Group. It comprises metagreywackes and conglomerates, with dykes exposed through thick coastal sand and a laterite cover at higher elevations. Two sites were studied (Fig.1). Location 1, near Sateri Ravalnath temple, hosts four dykes (CD-1 to CD-4), while Location 2, at Cacra beach below Laal Kothi, contains five (CD-5 to CD-9) (Table 1). Location 1 has thin laterite and thick sand, whereas Location 2 is marked by a thicker laterite cover. Both contain large laterite and dolerite boulders. The coastal setting exposes dykes to tidal influence; hence, observations were made under varying tidal conditions and after rainfall to ensure maximum dyke exposure.

Salient Observations

Field Observations

Nine dykes were identified along the Cacra coast, distributed across two locations. Location 1 hosts four dykes (CD-1 to CD-4), while Location 2 contains five (CD-5 to CD-9). These were examined under varying tidal conditions, revealing distinct submergence patterns. At Location 1, CD-1, CD-2, and CD-4 are partially submerged during high tide, while CD-3 remains completely submerged. At Location 2, CD-5 is partially submerged during high tide, whereas CD-7, CD-8, and CD-9 remain submerged even at low tide.

The dykes range from 2.5 to 15 m in thickness and 2 to 16 m in length, showing varied weathering due to tidal exposure. Location 1 dykes display advanced weathering with spheroidal patterns and joint-plane erosion, especially CD-2. Dykes at Location 2 are less weathered as they are partly shielded by landward exposure. Unconsolidated sand surrounds all dykes, with no visible country rock, and laterite boulders occur at higher elevations. Vegetation varies: dense inland at Location 1 and sparse at Location 2.

Table 1: List of the dykes showing their exposed length and width in the Cacra area

Sr No	Dyke	Length (m)	Width (m)
1	CD-1	12	2.5
2	CD-2	2	2.5
3	CD-3	16	11
4	CD-4	11.5	10.5
5	CD-5	9	3
6	CD-6	5.5	2.5
7	CD-7	10	3
8	CD-8	7.5	6
9	CD-9	8	3

Joint Pattern

The dykes exhibit distinct extensional joints with rough surfaces and open gaps. Most dykes show systematic joint sets, especially CD-3 and CD-4 at Location 1 and all at Location 2, where cross-cutting joints outnumber parallel ones. Due to the absence of exposed host rock, joint data were analyzed using Georose software. Rose diagram analysis (Fig. 2a-i) identified three major joint sets (NNE–SSW, NE–SW, and E–W) with minor trends in NE, NW, and N–S directions. CD-1 shows two main joint sets (NNE–SSW, NE–SW), though its trend was confirmed through geophysical survey. Other dykes show consistent trends: CD-2, CD-3, and CD-9 (ENE–WSW), CD-4 (NW–SE), CD-5, CD-7, and CD-8 (N–S), and CD-6 (NNW–SSE). These orthogonal, vertical to subvertical joints helped infer dyke trends in the absence of country rock.

Geophysical Survey of Dyke CD-1

The PQWT S300 instrument was used for 2D electrical profiling to record spontaneous potential differences at coordinates 15°27'06.4"N 73°50'02.8"E. The 40 m-wide area was surveyed to a depth of 150 m using 37 frequencies, taking about 1–1.5 minutes per node. With an accuracy of about 90%, the method effectively identified the dyke trend.

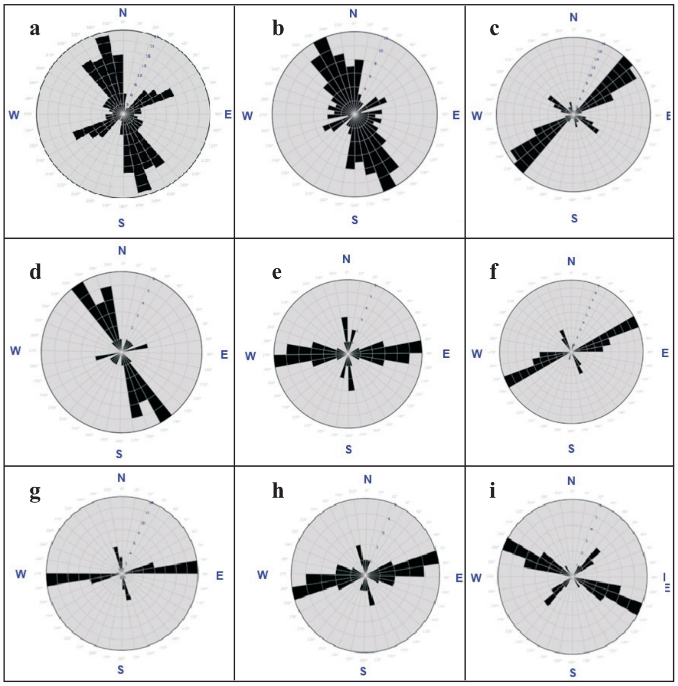

Fig.2. a-i: Rose diagram for CD-2, CD-3, CD-4, CD-5, CD-6, CD-7, CD-8 and CD-9.

Profiles L-270, L-273, and L-274 were taken in E–W and N–S directions. In Profile L-270 (Fig. 3a), the dyke was detected between nodes 7 and 9 with an exposed thickness of 2.5 m. Subsurface lithologies showed color contrasts: light blue (45–110 m depth) indicated saline water infiltration, while yellow to orange represented dry sand. Hard metagreywacke occurred at depth, confirming an N–S dyke trend. Profile L-273 showed a dip at node 5 corresponding to a visible field fracture, suggesting it is penetrative. Profile L-274 revealed a domical structure near node 5, possibly a shallow intrusive body influencing Dyke CD-1 (Fig. 3b).

Petrography

The Cacra dyke samples (CD-1 to CD-9) display coarse- to medium-grained, inequigranular textures with subhedral to anhedral mineral morphologies, indicative of hypidiomorphic fabric. The predominant minerals are plagioclase and clinopyroxene (augite), with opaques, biotite, chlorite, iddingsite, and quartz as accessory or alteration phases. Plagioclase commonly occurs as lath-shaped grains showing lamellar, simple, and penetration twinning, and often exhibits zoning (oscillatory in CD-1, CD-3). It occurs both as microphenocrysts and in the groundmass, suggesting bimodal crystallization. Alteration of plagioclase to sericite is frequent (CD-1, CD-3, CD-4), with grains occasionally showing undulose extinction (CD-5) and fracturing (CD-6). Pyroxenes (chiefly augite) display Carlsbad twinning (CD-3) and occupy interstitial positions between plagioclase laths, forming sub-ophitic, intergranular, nesophitic, and poikilitic textures (CD-1, CD-6, CD-7, CD-8, Fig. 4A–H). Symplectic intergrowths of plagioclase and pyroxene are frequent (CD-1, CD-3).

Alteration minerals such as chlorite (CD-2) and iddingsite replacing olivine (CD-5, CD-6, CD-7) are observed, indicating post-crystallization weathering. Biotite, showing pleochroism from pale yellow to dark brown, occurs as alteration rims around opaques (CD-2, CD-4). Opaque minerals occur as subhedral to anhedral, occasionally rhomboidal or equant grains, sometimes altered to biotite (CD-4). Among the dykes, CD-4 exhibits the highest opaque content (Fig.4D). Quartz appears sporadically as fine anhedral grains (CD-4). Characteristic textures across the suite include sub-ophitic, nesophitic, intergranular, intersertal, poikilitic, glomeroporphyritic, porphyritic, and symplectic (Fig.4A–I). Glomeroporphyritic clustering of plagioclase is particularly notable in CD-3, CD-5, CD-7, and CD-9. Interpenetrative textures, swallow-tail terminations, and coalescent plagioclase grains further indicate dynamic crystallization under variable cooling rates (CD-6, CD-7, CD-9). Micro-veins of glass occur locally (CD-8), showing no color change under plane- or cross-polarized light and marking possible reabsorption and annealing effects (Fig.4H). The dusty appearance observed in CD-2 and CD-4 thin sections results from advanced alteration.

Discussion

The mafic dyke swarm in the Cacra area of North Goa offers

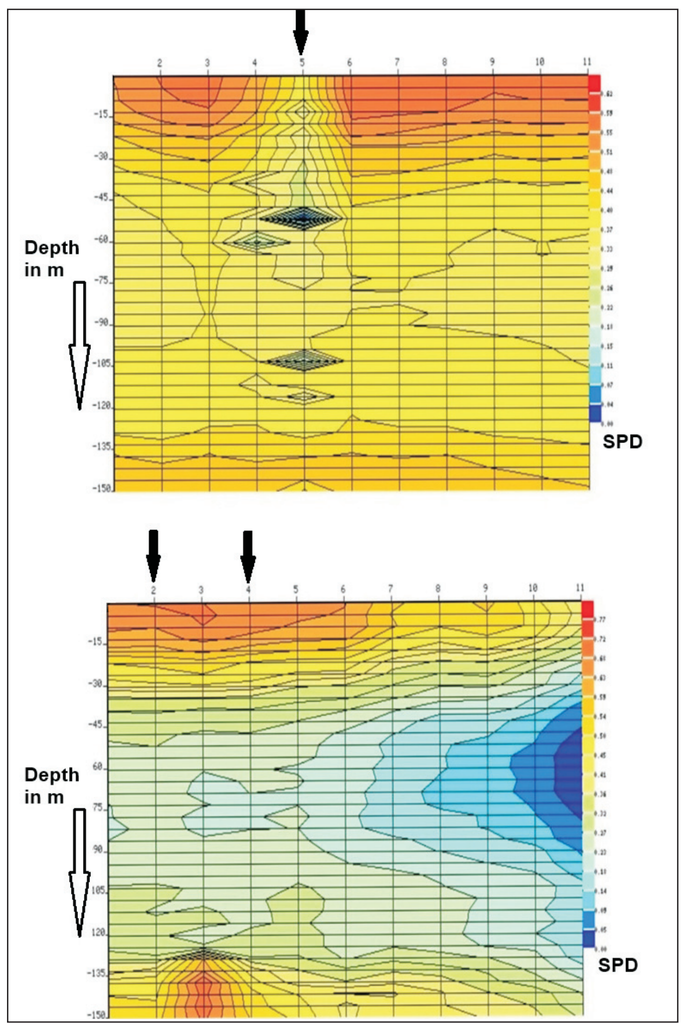

Fig.3. a. Vertical column indicating presence of dyke CD-1 between node 7 and node 8. Profile taken along E-W direction, **b.** Domical shape between node 2 and node 4 indicates probable intrusive body.

Fig.4. Photomicrographs of dolerite dykes (CD-1 to CD-9) under BXP and PPL (4×), (A) CD-1: Zoned plagioclase with porphyritic and sub-ophitic textures; sericitization noted, (B) CD-2: Chlorite and biotite showing weathered, dusty appearance, (C) CD-3: Augite with Carlsbad and penetration twins; symplectic and intergranular textures, (D) CD-4: Plagioclase altering to sericite with minor quartz; symplectic texture, (E) CD-5: Glomeroporphyritic and sub-ophitic textures; undulose extinction; olivine altered to iddingsite, (F) CD-6: Intersertal, intergranular, and nesophitic textures; coalesced plagioclase grains, (G) CD-7: Poikilitic texture with intersertal groundmass, (H) CD-8: Glassy micro-vein and nesophitic texture and (I) CD-9: Plagioclase laths penetrating augite; intersertal texture. *Abbreviations:* Pl–Plagioclase, Au–Augite, Opq–Opaque, Id–Iddingsite, Qtz–Quartz, Bt–Biotite, Chl–Chlorite.

insights into its orientation, petrography, and textures. Field studies show that the dyke's trend in ENE–WSW, NW–SE, N–S, and NNW–SSE directions, as determined using Georose and rose diagram analysis. Dyke CD1, with two major joint sets, required geophysical surveys to determine its trend. Although dyke host contacts are not exposed, metagreywacke is inferred as the country rock based on nearby exposures at Shirdona and drilling data from Dona Paula, which revealed metagreywacke at 45 m depth.

The dolerite dykes are medium grained and melanocratic, displaying porphyritic, ophitic, subophitic, and nesophitic textures. Subhedral plagioclase shows zoning due to incomplete calcium–sodium exchange, while irregular plagioclase–pyroxene contacts suggest simultaneous crystallization. Limited oscillatory zoning in plagioclase indicates stable crystallization conditions. The porphyritic texture reflects two stage cooling slow crystallization at depth forming phenocrysts followed by rapid cooling forming the groundmass.

Clinopyroxene phenocrysts are prismatic and fractured, and olivine is rare. Undulose extinction in plagioclase and glomeroporphyritic clustering indicate deformation and magmatic evolution. The abundance of plagioclase phenocrysts suggests early plagioclase crystallization, delayed pyroxene nucleation, and supersaturation leading to fine grained pyroxene in the groundmass.

Symplectic intergrowths between plagioclase and clinopyroxene indicate replacement during crystallization. Interaction of Mg, Fe, and Na with plagioclase led to albite formation, while Ca entered clinopyroxene, reflecting complex geochemical processes during dyke emplacement and cooling.

Conclusions

The mafic dykes exposed along the Cacra coast of North Goa represent multiple intrusive events emplaced along pre-existing structural weaknesses within the Proterozoic basement of the Dharwar Craton. Geophysical and structural analyses confirm variable dyke orientations, reflecting a complex stress regime during emplacement. Petrographic characteristics such as hypidiomorphic texture, mineral assemblage of plagioclase and clinopyroxene, and the presence of sub-ophitic and intergranular textures suggest crystallization from a basaltic magma under dynamic cooling conditions. The observed alteration and zoning features further indicate post-emplacement modifications and a two-stage cooling history.

Author Contributions

AS: Field Work, Methodology, Data Analysis and Data Curation, Writing - Original Draft Preparation. **PS**: Conceptualization, Investigation, Supervision, Funding Acquisition, and Editing, Revised Manuscript.

Conflict of Interest

The Authors declare that there is no conflict of interests.

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