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Regional Soil Patterns as Indicators of Late Cenozoic Change in the Critical Zone: A Baseline Synthesis for the Landscapes of Peninsular India

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Regolith across the South Indian shield has not previously been mapped. Here we provide a diagnosis of directional and lasting climate change from humid to semi-arid since the late Cenozoic based on evidence provided by mosaics of 1) residual, 2) colluvial and 3) alluvial soils across 700,000 km^2 of southern peninsular India. Results are inferred from a systematic geomorphological and palaeoenvironmental interpretation of 1:250,000 scale legacy soil maps at order to subgroup level, complemented by field surveys and controls of soil parent material—i.e., regolith. The inventory highlights two generations of residual soils: 1) deep Lixisols, hosting low-activity clays and large iron hydroxide concentrations indicative of humid conditions in the geological past; and 2) shallow Luvisols containing high-activity clays and large stocks of exchangeable bases, indicative of drier conditions compatible with the modern climate. Where still present, the relict Lixisol inliers straddle drainage divides and are in the final stages of being thinned or fully stripped by headward stream erosion. They are being replaced by the Luvisols over shallow weathering fronts. Colluvial and alluvial soils, including widespread Vertisols, are used as tools for detecting and mapping different generations of Quaternary flood deposits: fluvial terraces, coastal fan-deltas, and shallow upland palaeolakes. In a region mostly devoid of carbonate rock outcrops, the widely distributed pool of soils hosting abundant accumulations of pedogenic $CaCO_3$ also reveals the magnitude of silicate bedrock weathering as a process for generating secondary calcium carbonate in the rock cycle, thereby highlighting an under-appreciated contribution to inorganic carbon sequestration in the global carbon cycle. The results and maps produced provide exploration tools for future, more systematic and coordinated investigations of the nature and chronology of Quaternary deposits in peninsular India. This includes assessing their potential for hosting different generations of prehistoric archaeological remains.

Keywords: soil geomorphology, regolith, silicate weathering, spatial analysis, palaeoclimate, landscape evolution, carbon sequestration, soil fertility

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INTRODUCTION

The Critical Zone is an expression now commonly used to describe the thin, outer envelope of the Earth that uniquely hosts the terrestrial biosphere, and where soil and regolith operate as a gigantic geochemical reactor (e.g., Giardino and Houser, 2015): thus, while primary minerals feed into the reactor mostly from below through the weathering front and organic material is mixed in from above, solutes leak out into rivers and water tables and debris are removed from the topographic surface by erosion and redistributed across the landscape. The zone has been qualified as "critical" because it is the exclusive habitat of humankind while at the same time being exposed to the demographic and technological pressures of civilisation. Capturing the past, present and future states of the Critical Zone, therefore, is key to understanding its natural transformations, and potentially also to highlighting how modern, historic, or prehistoric societies have interacted or interfered with the resources hosted and ecosystem services provided by the Critical Zone.

The patterns and dynamics of the Critical Zone are best appreciated in specific geographical settings. Here we cast a wide, regional approach by providing a comprehensive analysis of the soil continuum of southern peninsular India, and by showing how the soil patterns document a multitude of continental-scale properties and processes relevant 1) to Cenozoic and Quaternary landscape evolution; 2) to the preservation potential of archives of past human or hominin presence; and 3) to the sequestration of inorganic carbon in secondary terrestrial carbonates.

The geology of southern India has been widely mapped and studied for its Precambrian structures, Mesozoic basins, Deccan flood basalts and related mineral resources (e.g., Roy and Purohit, 2018, and references therein), but only sparse information is available about the extent of Cenozoic and Quaternary regolith. We aim to redress this imbalance by producing a series of regolith reconnaissance maps across a continuum of six major Indian states, covering an area of ~700,000 km^2. The source material is a set of 1: 250,000 scale soil maps, enriched by exploratory field checks that have provided ground truth evidence for selected features of interest. The results afford insights into regional patterns of landscape evolution, and corresponding maps can be used as systematic exploration tools for planning sampling strategies and conducting baseline investigations into Quaternary geomorphology, past environmental changes, geochronology, and archaeology.

Regolith is the entire unconsolidated or secondarily recemented cover that overlies coherent bedrock (Graham et al., 1994; Stolt and Baker, 1994). It is typically generated by *in situ* weathering of the bedrock, thereby forming saprolite, but regolith also describes material that has been eroded, transported, and deposited as sediment. Regolith is older than the soils derived from it and often geologically much younger than the underlying rock. In low-energy cratonic environments, regolith is often relatively thin (≤5 m), but it can locally attain thicknesses of tens of metres. In peninsular India, stratigraphic sections in Quaternary regolith have more often been discovered and analysed by archaeologists than by geologists (reviews in Wadia et al., 1995; Korisettar and Rajaguru, 1998; Pappu, 2001; Rajaguru et al., 2009; Dennell, 2023). Those well-documented archaeological landscapes nonetheless remain small islands in a vast expanse of undocumented territory calling for more systematic reconnaissance. Mapping and characterising regolith is thus highlighted here as an important step towards 1) documenting the drivers and chronology of landscape evolution; 2) assessing the likelihood of finding different generations of buried prehistoric sites; and 3) appreciating the contribution of landscape-scale silicate weathering to Earth's thermostat by carbon sequestration—here in a stable cratonic environment.

Given that the properties of soil constituents change with time following fairly predictable pathways, soils can be used as tools for estimating the relative age of land surfaces. Three broad categories of soil can assist in interpreting land surface age: residual soils, which are expected to develop on interfluve summits and low-gradient slopes; colluvial soils, which occur on steeper slopes and tend to be well stirred by biological and physical process; and cumulic soils, which aggrade episodically from material added at the top, for example, in alluvial settings. Soil mosaics thus reflect differences in landscape dynamics, and their characteristics can potentially be used to infer past climate changes, periods of relative landscape stability, and the nature of ancient environments. Differences driven by climate change will be most pronounced on low-gradient slopes where soil residence times are sufficiently long to reveal the influence of climate. Young, incompletely developed soils that have a faint A horizon (e.g., Entisols in the U.S. Soil Taxonomy) or a weakly developed B horizon (e.g., Inceptisols) are also of potential interest because they are more likely to reveal differences in parent material and regolith than in the case of more mature residual soils. Lastly, calcite, silica, or iron oxide cements also accumulate at depth in some soils, adding mechanical strength and allowing the formation of distinctive erosion-resistant landforms—typically duricrust-capped plateaus, where the soils uniquely behave like hard rock. In some cases, and given time, this may promote topographic inversion of a previously low-lying area to an elevated position in the landscape. By having remained at the surface since their formation under climatic or hydrological conditions different to those that prevail today, such ancient soils qualify as relict soils or paleosols, and thus also contain key information for understanding landscape chronology.

By showing how broad groupings of slope and valley deposits can be inferred from the characteristics of the soils hosted by those landforms, soil geomorphology has previously delivered conclusive work in mid-latitude (Birkeland, 1999) and tropical environments (Bertrand et al., 1985; Bourgeon, 1989; Bourgeon, 1994; Bourgeon, 2001; Bétard and Bourgeon, 2009). Relative age estimates of soil–landform units on that basis can subsequently provide the framework for dating organic or mineral constituents using radiometric techniques, and produce robust age constraints on landform chronosequences (e.g., Delmas et al., 2015; Delmas et al., 2018; Diaz et al., 2016).

As a densely populated nation with economic priorities set on growing food crops, most of the Indian subcontinent has benefited from extensive, systematic soil mapping since the 1980s (Bhattacharyya et al., 2013). One important drawback is that the existing soil maps remain available only as paper sheets, whereas the advent of soil reference base digitisation elsewhere (e.g., Gray et al., 2009; Gray et al., 2011; Batjes et al., 2020) is taking soil classification and mapping forward to a growingly modular and user-defined understanding of soils (e.g., Omuto et al., 2013), thereby allowing continental-to local-scale distributions of individual soil properties to be mapped separately—e.g., texture (clay, silt, sand content), pH, cation exchange capacity (CEC), carbon content, base saturation, permeability, or water storage capacity. Thus, while digital soil mapping is gaining traction internationally, particularly under initiatives by French (Arrouays et al., 2014) and Australian scholars (Kidd et al., 2020), access to fine- or mesoscale soil map information in digital format is not readily possible for India as opensource data. This is confirmed by the content of the global gridded soil information database SoilGrids (Poggio et al., 2021), which can generate predictive models of the spatial distribution of soil properties worldwide when fitted to a training set of ~240,000 soil profiles and a series of environmental covariates: the SoilGrids dataset does not cover India entirely or systematically. Likewise, only 199 standardised soil profiles for the entire country have been made available to the World Soil Information Service—WoSIS, which compiles soil data for purposes of global soil mapping and modelling (Batjes et al., 2020). The recently released "legacy national-scale digital map of key soil properties in India" (Reddy et al., 2021) additionally confirms 1) that soil profile densities in the legacy database (see **Figure 1** therein) are lowest in southern India—which is the region of interest for this study; and 2) that the key focus of Indian soil mapping remains crop production and agro-ecological zoning rather than Earth-science applications.

Suitable soil maps for southern India nonetheless exist, and this study aims to explore their potential as proxies for 1) analysing the covariation of selected soil properties, and for 2) understanding regolith patterns and Quaternary sediment dynamics and past environmental changes. Indian soil maps follow Soil Taxonomy (latest update: Soil Survey Staff, 2022)—the U.S. classification which divides world soils into orders, suborders, great groups, subgroups, and series. The Indian surveys have recognised 103 suborders nationwide. Given that the analytical protocols of Soil Taxonomy do not document rock materials occurring deeper than a standard cutoff depth of 2 m below the land surface, the potential for using pre-ordained soil maps as proxies for mapping and understanding patterns of regolith in relation to landscape evolution would initially appear limited. However, we will show that there is headroom for using the Soil-Taxonomy-inspired maps as guides for 1) capturing some fine-scale spatial characteristics of regolith over extensive areas, and thus for 2) generating thematic maps and using them as exploration tools for crafting scenarios of landscape evolution and other Earth-science- and archaeology-focused purposes.

A synthesis of this reconnaissance work for southern India is the main goal of this paper. The baseline map data are intended as a platform 1) for scoping multidisciplinary research at the intersection between pedology, geomorphology, drainage network dynamics and past climatic environments spanning the late Neogene to the Holocene; 2) for interpreting changes in land occupation patterns by successive generations of humans or archaic hominins across the subcontinent based on the spatial distribution of colluvial and cumulic soil parent materials likely to host archaeological sites; and 3) for assessing the magnitude of ecosystem services such as inorganic carbon capture through $CaCO_3$ precipitation as a result of silicate rock weathering under a semi-arid climate where monsoon influence has been shielded) for many millions of years by the Western Ghats (**Figure 1**)—the large rifted-margin escarpment that stands in the path of summer monsoon airflow (Gunnell, 1997; Gunnell et al., 2003). We show that clear directional change in the landscapes and palaeoclimates of southern India can be reconstructed from evidence inferred from soil patterns, and from the relative distribution and abundance of indicator minerals in the soils such as kaolinite and calcium carbonate. Results call for a more systematic and coordinated investigation of the cratonic environments of India, where knowledge about regolith has tended to be piecemeal and report-based rather than systematic and survey-driven.

MATERIALS AND METHODS

Data Sources

The modern states of Maharashtra, Karnataka, Andhra Pradesh, Telangana, Kerala, Tamil Nadu and the territories of Goa and Pondicherry (**Figure 1**) are fortunate in having benefited from systematic, 1:250,000 scale soil-resource mapping (e.g., Challa et al., 1995; Reddy et al., 1996; Natarajan et al., 1997; Shiva Prasad et al., 1998; Harindranath, 1999). Each state totals between 120 and 400 soil family associations, collectively distributed across the study area among thousands of map units. A soil family association consists of a dominant soil category (>50% of the map unit's surface area) and a subdominant soil type (between ~20% and 50%).

In principle, the production of each map by the Soil Survey of India observed a succession of steps beginning with photointerpretation from Landsat imagery, followed by interfluve outlining, field surveys, and laboratory investigations of soil samples. Sehgal (1990) describes how soil–landform associations are outlined across a 1: 250,000 scale topographic sheet and complemented by gridded soil profile studies in the field at intervals of 10 km. For a state the size of Karnataka, for example, (192,000 km^2), a total of 4,900 soil observations were made by the survey teams, i.e., one detailed soil characterisation for every 38 km^2. For Kerala, Andhra Pradesh/Telangana, Tamil Nadu,

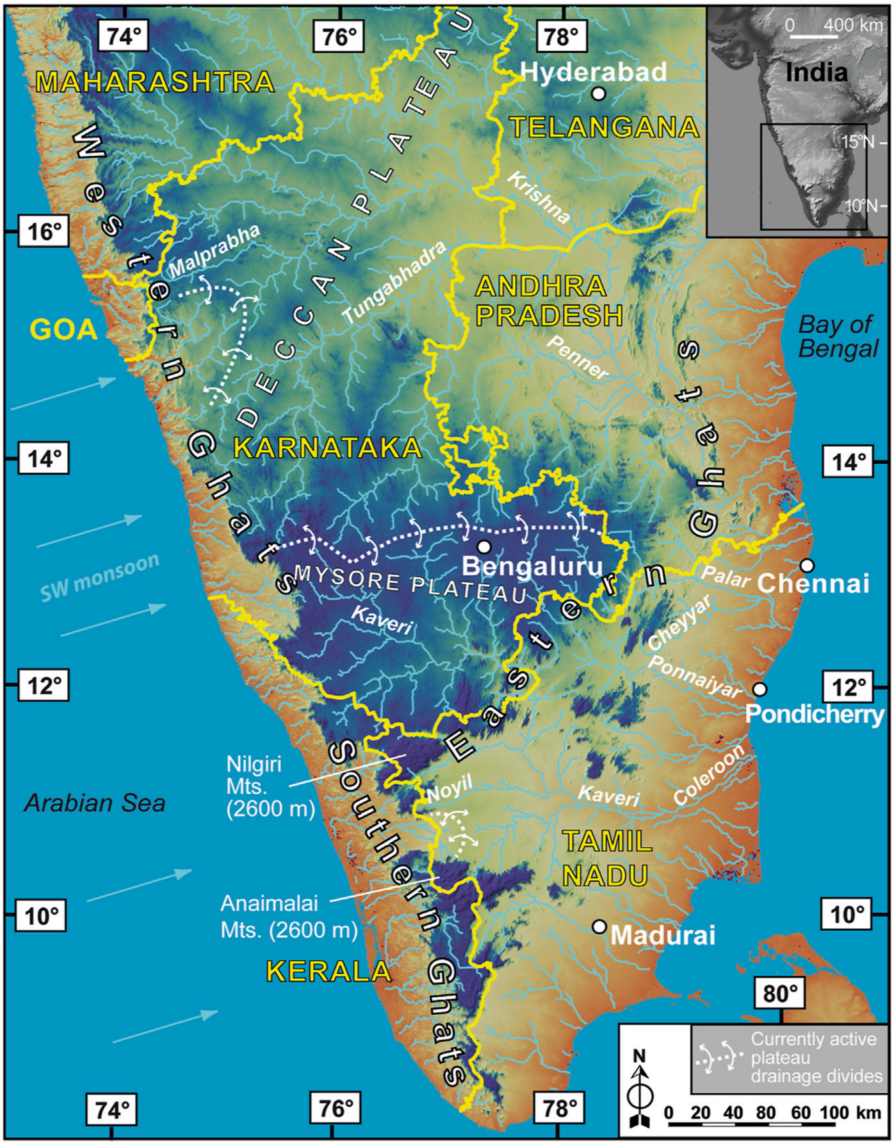

FIGURE 1 | Relief, drainage, and state boundaries of southern India. In this weathering-limited environment, areas of greater relief reveal the lithological contrasts and geological structure. Elevation source: ALOS World 3D digital elevation data (~30 m ground resolution). Blue colours highlight the Deccan uplands, with its highest region, the Mysore Plateau, in southern Karnataka (darker blues). The highest summits of the region are indicated (Nilgiri, Anaimalai). Tamil Nadu is mostly an erosional lowland, separated from the Mysore Plateau by another topographic escarpment—the Eastern Ghats.

and Maharashtra, likewise one full soil characterisation on average for every 25, ~27, 30 and 45 km^2, respectively. The soil maps thus constitute a good initial basis for understanding spatial patterns of dominant or subdominant soil orders, suborders, great groups, and subgroups.

Some of the soil profile attributes are explicitly provided in the map legend, such as soil depth, particle-size characteristics, surface texture, landform slope, etc. Others, such as colour, CEC, exchangeable bases, dominant clay mineralogy, etc., are implicit in the soil classification nomenclature itself, which requires a skilled understanding of Soil Taxonomy. Other soil properties of primary importance to agriculture, but of secondary importance to Earth science, were ignored. Given that the map information was not available as an opensource GIS database, the document sources used for the present study were printed map sheets, requiring to be manually digitised. A few of these sheets are currently available for inspection from the European Soil Data Centre.[1]

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[1] https://esdac.jrc.ec.europa.eu/

Note that Soil Taxonomy names are used in this study for purposes of traceability to the data sources—i.e., the original maps and their handbooks—and for repeatability of the interpretations. For readers unfamiliar with Soil Taxonomy and its classification criteria, **Supplementary Material S1** provides a systematic inventory of the soil taxa encountered in this work at order, suborder, great group and subgroup levels, with indications of their defining characteristics and corresponding names in the widely used Reference Base for Soil Resources (WRB) lexicon.

Classification of Map Units Based on Soil Minerals or Parent Materials

Given the characteristics of the Indian craton, where sedimentary archives are scarce compared to regions where young volcanic deposits, aeolian sediments, or stairways of alluvial terraces in deeply cut valleys occur, information about palaeoenvironmental signatures and landscape changes was gained by targeting three soil classes bearing highly contrasting mineral characteristics: young colluvial or cumulic soils hosted by geologically recent depositional parent materials, kaolinitic residual soils, and calcareous soils—whether residual or otherwise.

Kaolinitic soils are defined by Soil Taxonomy as containing, by weight, more than 50% kaolinite, halloysite, and other 1:1- and non-expanding 2:1-layer minerals in the clay-size fraction (<2 μm). Being diagnostic of humid tropical weathering conditions, such soils can only result from the long-term residence of rock outcrops in a high-rainfall climate. When encountered in a semi-arid region today, these kaolinitic soils, which will also often display iron hydroxide enrichment (lateritic duricrust) in the weathering profile, must consequently classify as relict soils, or paleosols. As such, they are diagnostic of some past climatic change from wet to dry.

Calcareous soils indicate a comparatively more arid environment (e.g., Zamanian et al., 2016). Soil Taxonomy defines them as containing sufficient $CaCO_3$ to generate visible effervescence with cold dilute HCl. Calcareousness classes are given by Indian soil maps as strong (>25% $CaCO_3$), moderate (10%–25%), slight (2%–10%), and non-calcareous (<2%). "Calcic soils" are a special category of calcareous soils exhibiting a diagnostic horizon of soft powdery lime at least 15 cm thick and situated in the top 125 cm below the land surface. Note that calcic soils only match a restrictive definition of what is broadly defined as calcrete given that thick calcrete profiles are not exclusively pedogenic but can be produced by multiple, simultaneous or sequential interactions that include groundwater and wind-blown dust (e.g., Durand et al., 2006a and references therein). Nevertheless, soil calcareousness is an indicator of widespread pedogenic carbonate occurrences—hence the value of also mapping calcareous soils as an exploration tool for investigating environmental signatures over a large territory.

Relative Age of Soil Map Units Inferred From Polygon Pattern Analysis

Getting closer to identifying the regolith materials hosting the soils required a wider array of criteria. Relative dating from maps is a time-tested method based on the principles of stratigraphy and cross-cutting relations between soil, rock, and/or sediment units in map view. It involves placing the map units in their proper sequence of formation (Daniels et al., 1971; Hall, 1983). Criteria will typically be based on map unit shapes, on relative map unit sizes, on their positions relative to the drainage network, and on their associations and collective patterns at various levels of aggregation or disaggregation. Interpretations are enhanced when this textural analysis of map unit mosaics is underpinned by a skilled understanding of landforms in relation to drainage catchments and geological outcrops. In the study area, extensive field reconnaissance has revealed that unweathered bedrock lies typically less than 50 m beneath kaolinite-rich soils, and merely 0.5–5 m beneath alluvial deposits. Alluvium thickness usually varies as a direct function of stream order, i.e., thicker alluvium is associated with larger rivers.

Linking soil associations to topography, drainage and landforms is a valuable tool for making statements about:

(i) where soils hosted by Quaternary flood or hillslope deposits, rather than by weathered bedrock, occur in the landscape;
(ii) where kaolinite-rich weathering profiles have subsisted in a semi-arid climate which is currently incompatible with abundant kaolinite neoformation;
(iii) where Ca-rich solutes get arrested in the landscape, and thus where calcrete profiles—which potentially contain palaeoenvironmental information and can be U–Th dated—may have developed.

In the present case, the consistent link between soil patterns, drainage, and topography was not initially obvious because Indian soil maps lack elevation contours and relief shading. ALOS World 3D digital elevation data (~30 m ground resolution, ~5 m vertical accuracy), drainage networks generated from the elevation models, and full sets of 1: 250,000 and 1:50,000 scale Survey of India topographic sheets were thus additionally used to check topographic relations between soil taxa, particularly across low-relief topography where field relations are inherently difficult to establish.

Aggregating subgroup-level soil map information and scaling it up to soil suborder level was found to be best suited to the purpose of understanding broad trends in palaeoenvironmental change and landscape evolution. The several thousand soil map units for all the maps of the study area were thus systematically inspected in search of the attributes listed above, using available criteria provided by the maps, their legends, and their associated handbooks. The relevant polygons were then digitised, selectively masking out all other irrelevant soil types in order to reveal patterns in the regional distribution of 1) kaolinitic residual, 2) alluvial and colluvial, and 3) calcareous soils.

RESULTS: AN INVENTORY OF REGOLITH MATERIALS DIAGNOSTIC OF CLIMATE-DRIVEN LANDSCAPE DYNAMICS

The maps in **Figures 2**–**9** display the results inferred from the source data, enriched by field observations and satellite imagery. This section provides commentary and interpretation of those different documents, and yields clues for understanding late Cenozoic and Quaternary landscape dynamics on the Precambrian shield. The driving questions of the investigation are:

(i) whether there is any systematic association between kaolinitic soils, calcareous soils, or younger soils (whether calcareous or non-calcareous, kaolinitic or non-kaolinitic) and particular classes of landforms;
(ii) what have been the sources for the $CaCO_3$ or the kaolinite in the soils;
(iii) what are the characteristics of soils that lack accumulations of either $CaCO_3$ or kaolinite.

The focus excludes structural bedrock landforms, apparent in the relief map of **Figure 1**, which are generally too steep to bear soils relevant to this study and which generally display Orthents (i.e., Letptosols and Regosols in the WRB lexicon).

Relative Distributions of $CaCO_3$ and Kaolinite in the Landscape

In southern India, aridity arises from a combination of low precipitation totals and a concentration of rainfall within just 3–4 months in the rainshadow of the Western Ghats (**Figure 1**). The driest core areas lie at the centre of the Deccan Plateau and in western Tamil Nadu, where annual rainfall does not exceed 600 mm (**Figure 2**). Despite the dry climate, the first-order soil pattern reveals a mosaic of 1) calcareous soils, which are mineralogically compatible with low rainfall, and 2) kaolinitic soils, which seem out of place given their affinity with humid climates (**Figure 2**).

Calcium-Carbonate-Rich Soils

$CaCO_3$ accumulation in the rainshadow of the Western Ghats is widespread (**Figure 2**), with the added paradox of extending across a region of Precambrian silicate rocks mostly lacking carbonate outcrops as potential sources of calcium (**Figure 3**). Soils of the relevant land units are either dry for more than 90 cumulative days or moist for fewer than 90 consecutive days, which contributes to incomplete leaching of calcium ions and results in the formation of calcic horizons. They display at least discrete $CaCO_3$ filaments, most often friable nodules and rhizoconcretions, but also thick, differentiated calcrete profiles with massive, entirely cemented carbonate hardpan containing 75%–90% $CaCO_3$ (see **Supplementary Material S2**). The states of Andhra Pradesh and Telangana, for example, together host 18% of moderately, and 10% of slightly calcareous soils, together covering an area of 77,000 km^2 (Reddy et al., 1996). Exposures provided by irrigation well shafts (see **Supplementary Material S2**) have further revealed that $CaCO_3$ accumulations also exist at deeper levels in relation to fluctuating water tables in the weathered Precambrian basement saprolite, indicating that a range of agencies have been involved in the process of $CaCO_3$ enrichment of the cratonic regolith.

Kaolinite-Rich Soils

The most striking feature amid the pervasive distribution of calcareous soils in the semi-arid interior of southern India is the existence of two regional enclaves of soils containing >50% kaolinite by weight (**Figures 2**, **4**):

(i) The largest anomaly (red circle, **Figure 2**) coincides topographically with the Mysore Plateau (**Figure 1**) and geologically with Precambrian gneiss (**Figure 3**). The soils classify as Lixisols or ferric Luvisols (WRB), i.e., “kaolinitic Kandiustalfs” (Soil Taxonomy). They are commonly capped by iron-enriched duricrust in various states of degradation, particularly east of the large metropolis of Bengaluru (Bangalore). The kaolinitic nature of the soils is incompatible with the present-day dry climates, under which rainfall currently exceeds potential evapotranspiration at best during only 1 month. This points to directional climatic change from regionally humid and laterite-forming to regionally drier conditions, thereby arresting lateritic profile development. The relative chronology of this climatic sequence is locally detectable in the stratigraphy of regolith and paleosol profiles encountered in the field (**Figures 4A–C**).
(ii) Another inlier of relict laterites occurs on the late Cretaceous Deccan flood basalts (**Figure 2**), and hosts the medieval fortified city of Bidar, where laterite is the predominant building stone (see **Supplementary Material S3**). Here, the corresponding soils were classified as “kaolinitic rhodic Paleustalfs” and “kaolinitic oxic Ustropepts” (Shiva Prasad et al., 1998). Unlike the Mysore Plateau outlier, where soils in the valley networks are conspicuously non-calcareous, the lower-lying map units lining the valley floors are fully invaded by calcareous soils (**Figure 2**). This contrast is related to differences in Ca content of the local bedrock, with CaO-rich flood basalts—CaO content of the Deccan basalts ranges from 9% to 14%: Widdowson and Gunnell. (1999)—but mostly CaO-poor Precambrian gneiss on the Mysore Plateau (see Bourgeon, 1994).

Classification of Regolith and Associated Land Systems Based on Soil Criteria

Black Soils (Vertisols) as Indicators of Fluvial or Lake Deposits

Vertisols are good indicators of the distribution of Quaternary alluvial deposits because they are generally associated with transported materials, and because they occur typically on slope gradients <5%—i.e., environments where surface ponding of water may occur for extended periods (e.g., Mermut et al., 1996). Vertisols thus overwhelmingly occur in

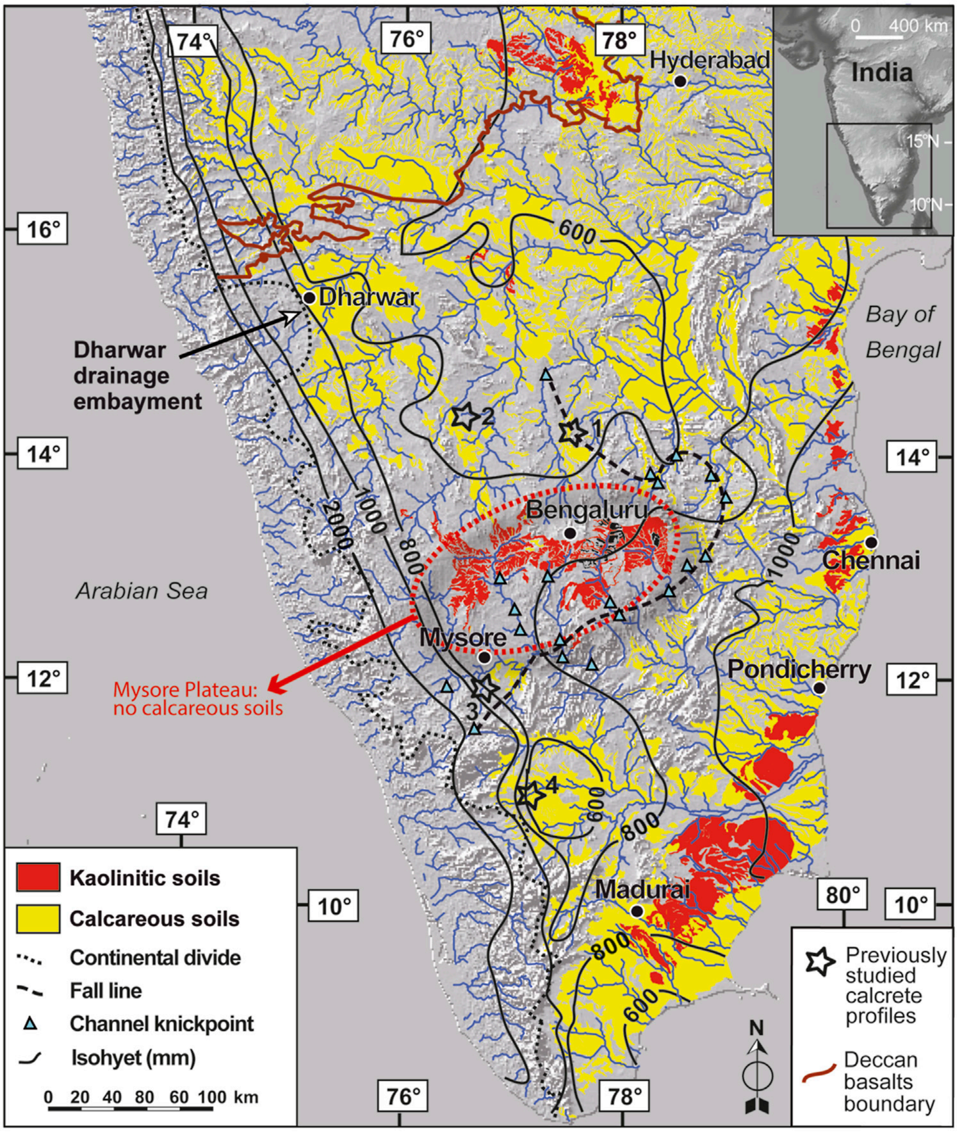

FIGURE 2 | Calcareous soils and their spatial relationship with kaolinitic soils in semi-arid southern India. Isohyets in millimetres. Numbered stars indicate documented calcrete study sites on Precambrian gneiss. Short-dash black line: continental drainage divide. Long-dash black line: fall line of the Eastern Ghats. Note that the Eastern Ghats escarpment is never a drainage divide. Map projection: transverse Mercator.

low-lying landscape positions that are periodically wet in their natural state and typically discourage leaching losses.

Figures 5, **6** illustrate the occurrence of smectite-rich Vertisols and provide a measure of their extent across the region. Their widespread distribution highlights the considerable extent of Quaternary overbank flood deposits resting unconformably on weathered cratonic bedrock. The abundance of smectite explains the manifestation of shrink-swell processes in Vertisols—a key property of their behaviour in response to cycles of wetting and drying. The field-verified finding that Vertisols are primarily hosted by allochtonous deposits rather than by *in situ* weathered bedrock clarifies a common misconception concerning the link between so-called Indian *regur* (equivalent of "black cotton soils" in the United States, i.e., Vertisols) and the Deccan basalts. Although basalt is a source of calcium and would explain Vertisol calcareousness, Vertisols do not commonly develop *in situ* directly from weathered basalt. Additionally, they occur extensively outside the flood basalt province, namely, on the Precambrian gneiss and metagreywacke (e.g., Rengasamy et al., 1978; Bourgeon, 1989; Bourgeon, 1992).

Pal et al. (1989), Pal et al. (2009), Pal et al. (2012) have reviewed the origin and distribution of Vertisols on basalt in India from the viewpoint of clay mineralogy, making inferences about palaeoclimate on the basis of secondary mineral abundance and stability within certain rainfall

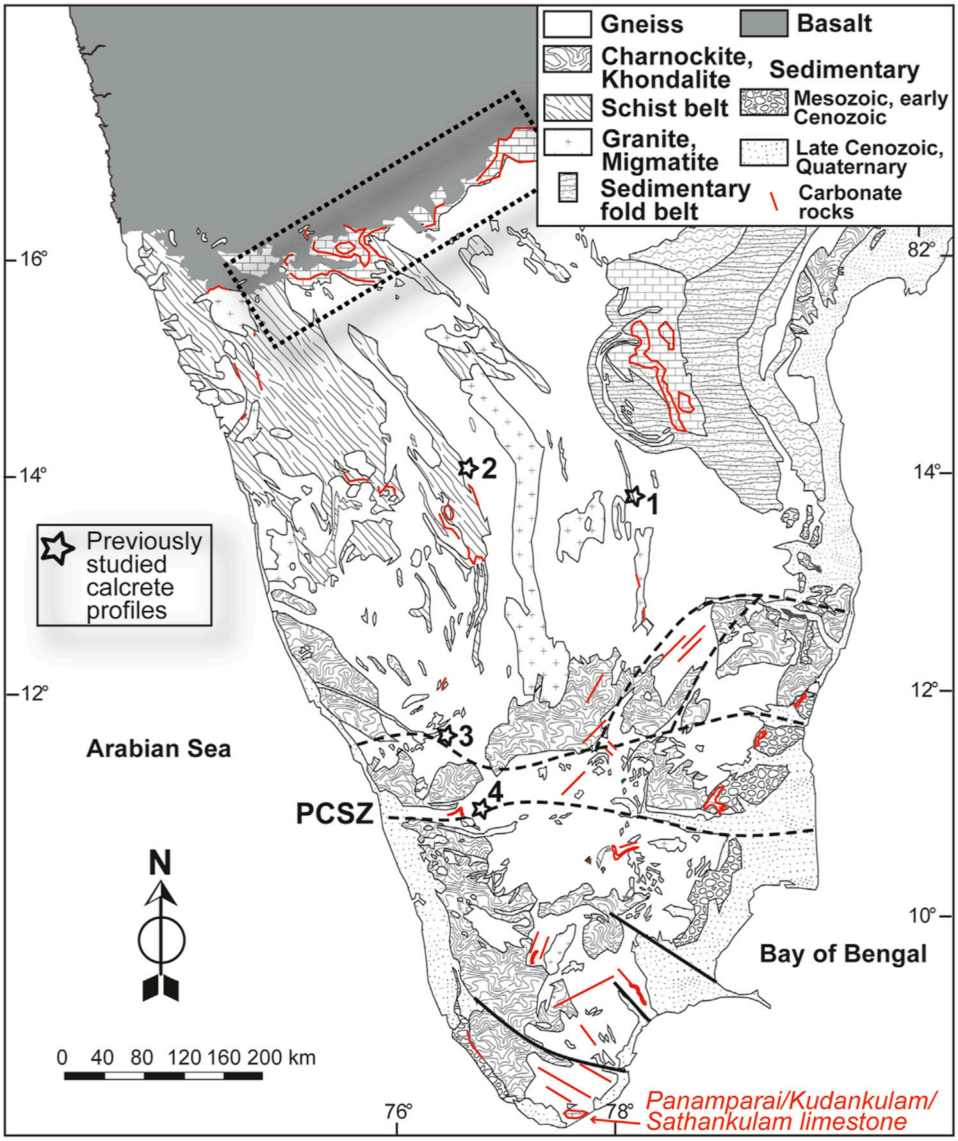

FIGURE 3 | Simplified lithostratigraphic map of the southern Indian shield. Brickwork ornament: Proterozoic limestone. Bold black lines or outlines: Precambrian carbonate rocks in red are anorthosites, carbonatite dykes, and thin metamorphic limestone bands. Dashed lines: outline of major Precambrian shear zone. Numbered stars: as in **Figure 2**.

brackets. Conditions favourable to the formation of smectite occur where base-rich aluminium silicate minerals weather under moderate leaching. On plagioclase-rich Deccan basalts, dioctahedral smectite is the first secondary mineral to form given the relatively high concentrations of constituent cations (Mg in the case of montmorillonite) and silica in the soil solution.

At landscape scale, soil catenas from hilltops to valley floors highlight the confinement of Vertisols to low-lying areas of the topography. On the Deccan basalts, for example, the soil maps suggest the following geomorphological connections:

(i) residual soils capping elevated volcanic mesas are very shallow (thickness: <15 cm), loam- and clay-textured, and dark-coloured. They are immature, poorly differentiated and often stony soils mapped as Inceptisols or Entisols ("lithic Ustorthents," "lithic Ustropepts"; Challa et al., 1995). By definition, Inceptisols may display at best a cambic horizon, i.e., subsurface layers of pedogenic change lacking appreciable indicators of illuviation;

(ii) colluvial soils on gentle slopes (depth <90 cm) are "medium black soils." These are dark greyish-brown or dark grey, and clay- or silt-textured. They qualify as "vertic

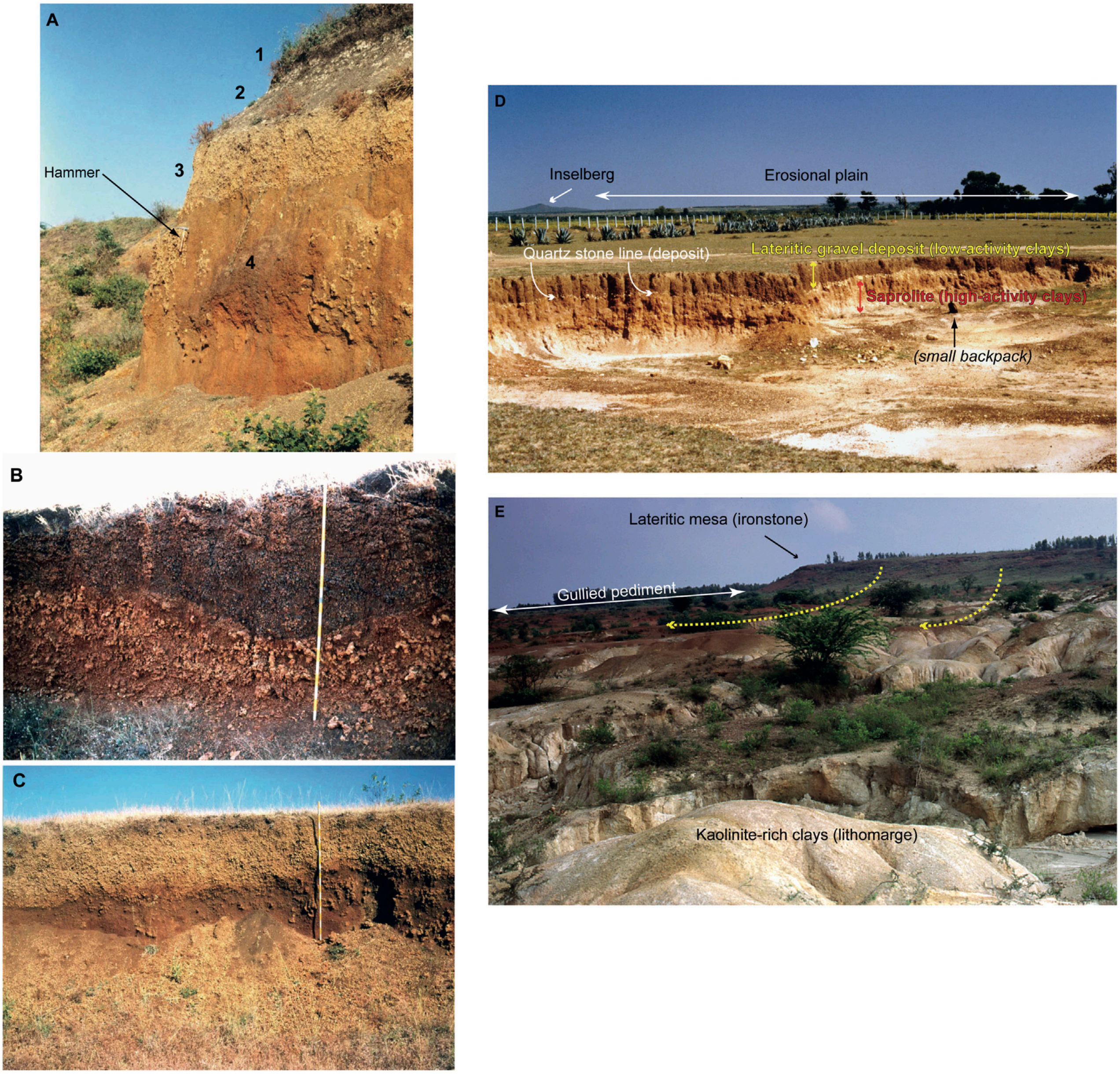

FIGURE 4 | Paleosols encapsulating the history of climate change on the cratonic upland interior of the Deccan (north Karnataka, elevation: 650 m, annual rainfall: 600 mm). **(A)** The dark top of the profile is a Vertisol (1) displaying nodules of chalky calcrete. Its parent material is a Quaternary floodplain deposit resting unconformably on the underlying levels. Lower down (2), whitish patches indicate the presence of illuvial $CaCO_3$. The indurated whitish B horizon below (3) consists of coalescing stringers and nodules of pedogenic calcrete. It outlines the mean wetting depth in this climate and forms a geochemical barrier to Ca mobility in the landscape. The three levels together are indicative of a semi-arid climate and overlie a fossil laterite (4). This iron accumulation could only develop under humid climates and cannot be the parent material from which the Vertisol developed. The laterite is no longer in equilibrium with the current dry climate. The laterite has been preserved because of its intrinsic hardness and because the surrounding landscape is a low-energy, low-gradient topographic environment. **(B,C)** Two other cases of calcrete invading a fossil laterite duricrust in central Karnataka. **(D)** A duplex soil occurrence north of Hassan, southern Karnataka, where the weathering profile on gneiss contains high-activity smectite and illite and is thus compatible with modern semi-arid conditions, but where a thin cover of lateritic and vein-quartz gravel indicates erosion of a lateritic landform (likely similar to the mesa shown in illustration **(E)**, and deposition of the debris over the saprolite and currently active weathering front. The source area for this lateritic material is no longer detectable in the landscape. **(E)** Example of a residual lateritic mesa and underlying, kaolinite-rich weathering profile along the drainage divide east of Bengaluru. Yellow arrows indicate transport by rillwash of lateritic debris (pisoliths) from the caprock outcrop across the wash pediments of the surrounding landscape, eventually resulting in a stratigraphy similar to the example shown in illustration **(D)**. **Figure 11** links these different regolith profiles into a landscape evolution scenario. Photograph credits: Y. Gunnell.

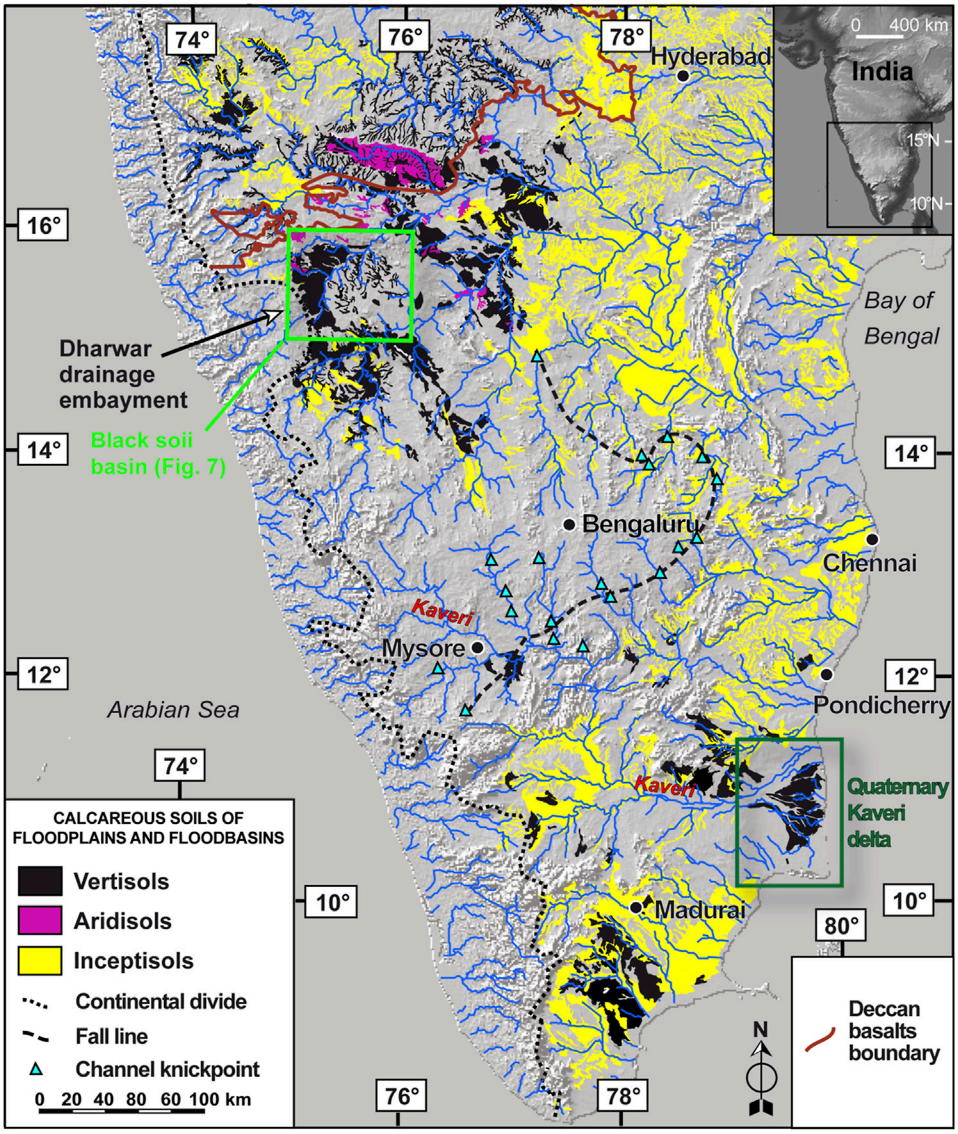

FIGURE 5 | Calcareous soils of valleys and floodbasins. The Vertisols in the source maps correspond to various subgroups of the "Chromustert" group, or to "typic Pellusterts." The Aridisols classify as ustollic Calciorthids. Inceptisols here cover the subgroups of typic, vertic and fluventic Ustropepts. Map projection: transverse Mercator.

Ustropepts," "ustollic Calciorthids," and "Chromusterts" (see **Supplementary Material S1**).

(iii) only the deep black soils (depth >90 cm) flooring fluvial valleys qualify as mature Vertisols ("typic Chromusterts", "Pellusterts"); they contain >60% clay—mostly smectite–are dark greyish-brown to very dark grey, and are hosted by alluvium.

An abundance of Vertisols in the semi-arid landscapes of southern India is an apparent paradox because smectite neoformation rates in dry climates are slow, and because smectite in weathering profiles is unstable under humid conditions and eventually transforms to kaolinite. The key to understanding the occurrence of large expanses of smectite-rich Vertisols lies, however, in adopting a catchment-scale perspective: alluvial deposits in seasonally dry cratonic regions are rich in smectite mainly because drainage systems have been eroding extensive catchment areas where smectite formation is prevalent on interfluves. Smectite-rich clay particles are accordingly deposited on the floodplains of intermediate- to high-order streams. Smectite thus concentrates selectively on valley floodplains, where it is stored and becomes incorporated into post-depositional pedogenesis. Smectite also forms where groundwater containing Mg^{2+} and H_4SiO_4 drains from higher areas

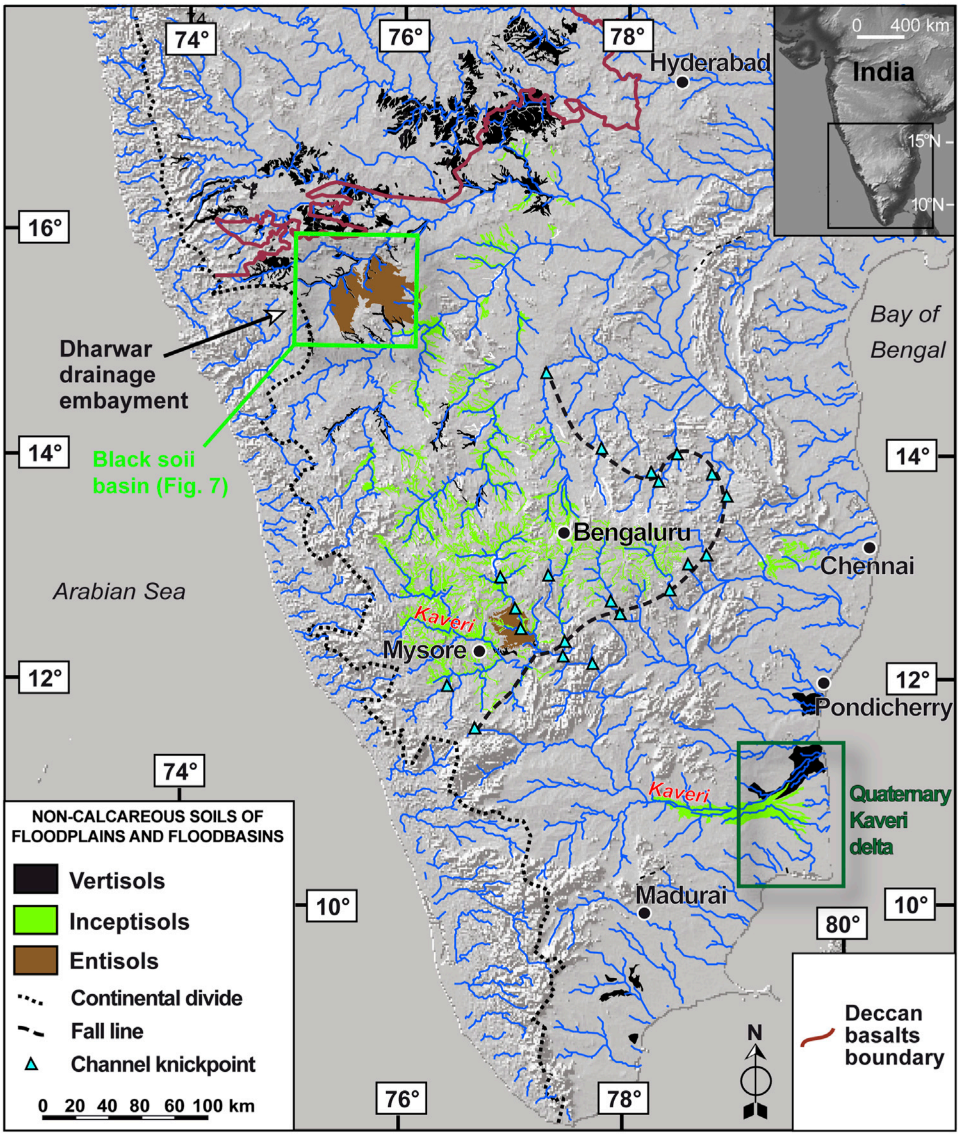

FIGURE 6 | Non-calcareous soils of valleys and floodbasins. The Entisols classify as lithic Ustorthents. The Inceptisols are either "typic" or "vertic Ustropepts," or "typic Ustifluvents." Linear ornaments: as in **Figure 5**. Thick dashes: boundary between older calcareous valley soils (to the west) and younger non-calcareous valley soils (to the east), reflecting a major hiatus—a fall-line of migrating channel knickpoints—related to drainage integration as it operates currently inboard of the Eastern Ghats escarpment. All of these soil occurrences denote younger parent deposits than those of **Figure 5**. Map projection: transverse Mercator.

and collects in low-lying areas where relative concentrations of those constituents increase as a result of evapotranspiration. Poor drainage and seasonally waterlogged conditions typical of floodplain or shallow lake environments further ensure conditions under which stabilisation of smectite is possible (Jackson, 1965; Kantor and Schwertman, 1974).

As shown in **Figures 5**–**8**, Vertisols occur as three contrasting map-unit shapes: 1) large, compact patches; 2) elongated ribbons along larger valleys or floodways; and 3) fine dendritic networks. The patches represent two types of geomorphic setting: deltaic floodplains, particularly the Kaveri River delta (dark green box in **Figures 5**, **6**), in Tamil Nadu; and broad, ancient floodbasins—perhaps functioning intermittently as shallow palaeolakes—in the northern uplands of Karnataka. In NW Karnataka, a conspicuous continuum of Vertisol and Entisol map units (light green box in **Figures 5**, **6**) probably corresponds to a former palustrine floodbasin, at one time sustained by the overflowing, monsoon-fed Malprabha and Tungabhadra rivers (see **Figure 7**). Ribbons of Vertisols define the treads of active or abandoned river floodplains. When these ribbon-shaped soil units are themselves bisected by dendritic networks of narrower, inset channels floored by immature soils (e.g., Inceptisols), chances are that the wider Vertisol-capped ribbon is an alluvial terrace incised by a narrower floodplain.

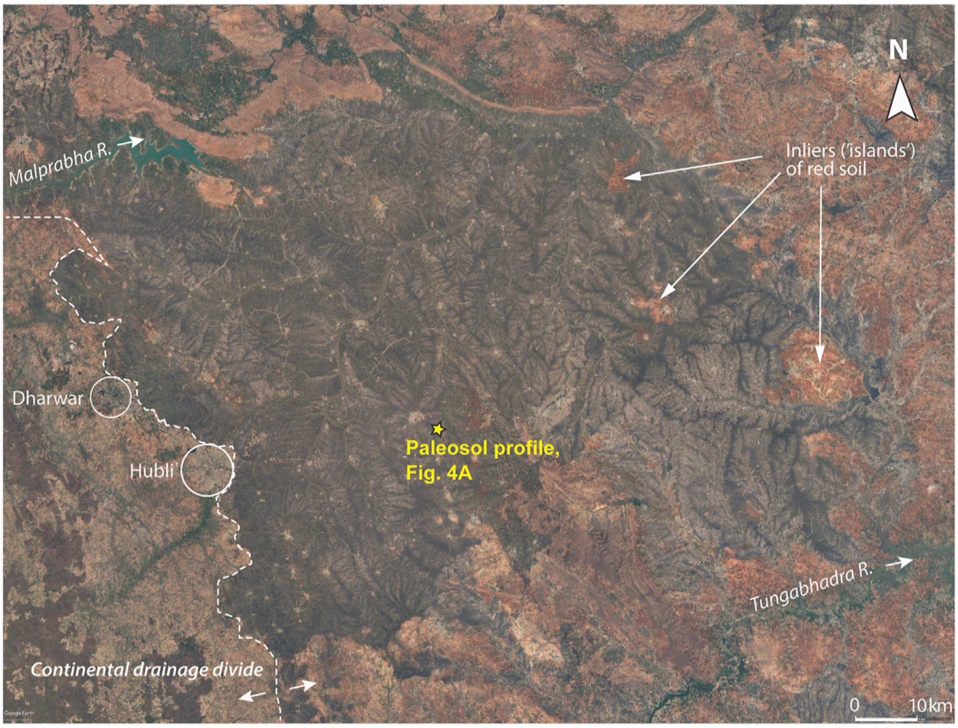

FIGURE 7 | Vertisol-filled basin hosted by Precambrian silicate bedrock: a possible palaeolake. Location box in **Figures 5**, **6**. The extensive black-soil basin east of the migrating Dharwar–Hubli continental drainage divide suggest a Quaternary palustrine floodplain environment bridging the Malprabha and Tungabhadra river floodways (Landsat/Copernicus image, from the Google Earth navigator). The dominant soils in the west are deep calcareous Vertisols (mapped in **Figure 5**), transitioning eastward to a soil family association consisting of: 1) thin Entisols (brown map unit in **Figure 6**, which consists of lithic Ustorthents, i.e., by definition less than 50 cm thick immature soils on young deposits resting unconformably on the weathered Precambrian basement); and 2) 20%–50% of deep montmorillonitic Vertisols. Sharp boundary between black (east) and red (west) soils along the continental drainage divide suggests that the basin may have extended farther to the west but has been recently amputated by actively receding headwaters from the Arabian Sea through gorges in the Western Ghats. White circles: urban centres.

Based on these criteria, a basemap of alluvial terraces—currently unavailable for southern India—can be generated.

Calcareous and Non-Calcareous Soils: Their Distribution as a Function of Topography

Here we proceed to distinguish between three classes of soil: 1) calcareous colluvial or cumulic soils where parent materials are in all likelihood Quaternary deposits; 2) non-calcareous colluvial or cumulic soils; and 3) residual soils, whether calcareous or non-calcareous, occurring on saprolite-mantled wash pediments and interfluve summits lacking Quaternary deposits.

Immature Calcareous Soils on Valley Floors

Elongated map units of calcareous soil, which typically highlight drainage networks in **Figures 2**, **5**, clearly indicate that $CaCO_3$ has accumulated in alluvium flooring river floodpains, and on footslope colluvial aprons. The widths of these linear map units are roughly proportional to stream order. Corresponding soil attributes are indicated by map legends as clay- or loam-rich textures, which are typical of suspended-load alluvial sediments where floodplain aggradation occurs by overbank flow. Given the high (>30%) content in clay minerals, many of the soils encountered on this fine-textured alluvium are Vertisols (**Figure 5**). The other calcareous soils of low-lying areas are mostly Inceptisols, and thus—by definition—young soils in the process of developing on recent sediment (Buol et al., 1989). The map legends describe them as "moderately deep to deep clay or cracking-clay soils with high base saturation (50%–80%) and high CEC." Calcareousness and texture vary somewhat—some are gravelly clay soils, indicating a mixed-load alluvial deposit. Some occurrences are explicitly defined as montmorillonitic, i.e., containing >50% smectite by weight. Such variability is to be expected in the context of variably textured colluvial and alluvial deposits.

A focus on different areas of Tamil Nadu will help to illustrate the cross-cutting relations between different categories of calcareous and non-calcareous soils. In the Kaveri delta area, for example, three landscape units can be distinguished:

(i) large areas of "calcareous Vertisols" (**Figure 5**) appear to coincide with the older, more stable outcrops of interdistributary silts and muds, now abandoned and

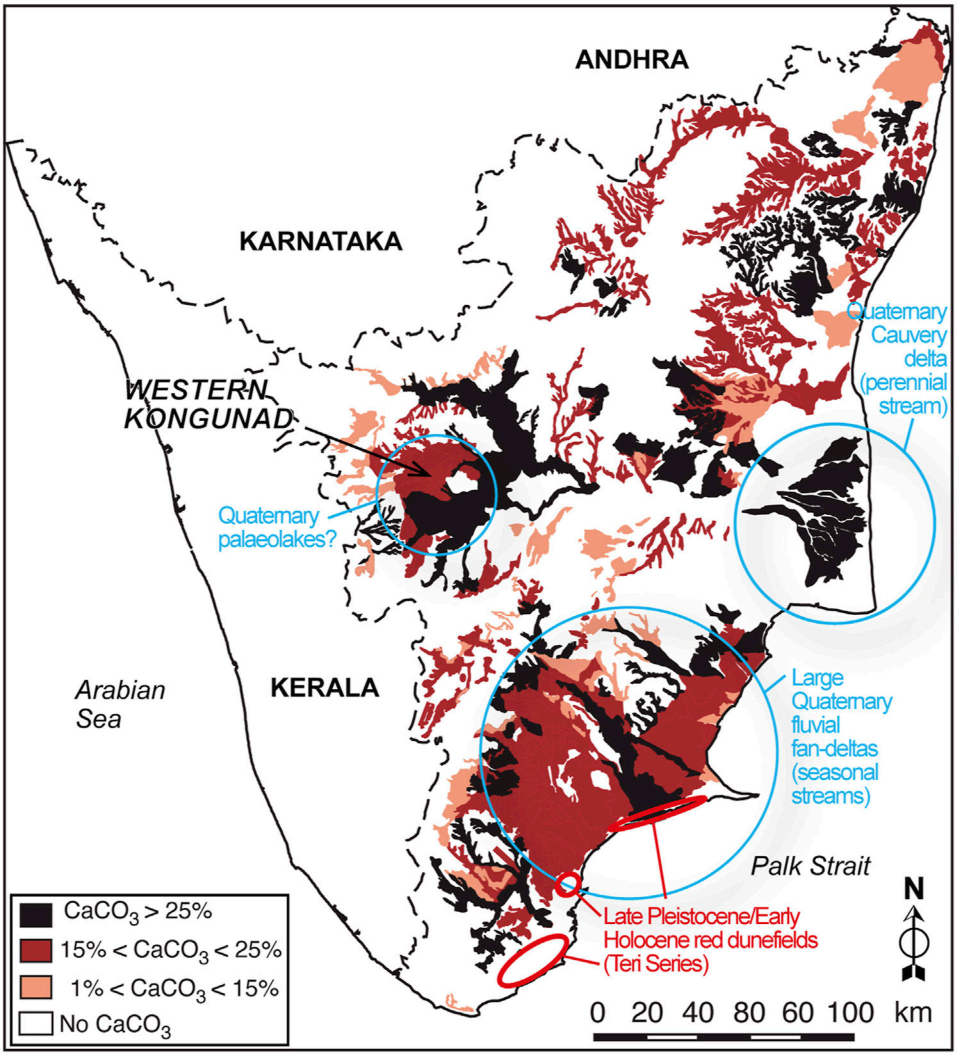

FIGURE 8 | Soil calcareousness classes and associated Quaternary landforms inferred from the soil outcrop patterns in Tamil Nadu. Polygon shapes evoke past and present river networks and their floodplains or floodbasins, but also possible paleolakes in western Kongunad and fluvial fan-deltas in SE Tamil Nadu.

incised by cross-cutting map units belonging to units (ii) and (iii) described below;

(ii) a comparatively younger, cone-shaped feature corresponding to a "non-calcareous vertic Inceptisol" occurs in the north along the most active delta-margin distributary of the Kaveri River and known as the Coleroon (map unit appears in black in **Figure 6**);

(iii) soils capping a third generation of even younger sediment in the active inner-deltaic floodplain and its distributaries. These immature soils classify as Fluvents (map unit appears in green in **Figure 6**) and correspond to the currently active floodplain.

In sum, Vertisols on older alluvial deposits, when near marine base level such as in the Kaveri delta, are calcareous; meanwhile, younger soils on the active floodplain of the Kaveri River, which is the only perennial stream of Tamil Nadu, are non-calcareous. These non-calcareous soils are all young and poorly differentiated, and accordingly classified as Entisols (Fluvisols in the WRB lexicon) hosted by palaeochannel bedload deposits—chiefly sand; or as Inceptisols, i.e., clay-rich, with vertic properties, corresponding to floodplain environments dominated by overbank flooding and laminar flow. Soil calcareousness in these depositional environments of the Tamil Nadu lowlands is thus potentially an indicator of the relative frequency of disturbance by flooding: whereas areas less frequently exposed to floods—typically clay-rich overbank floodbasin environments—provide alluvial deposits with greater opportunities for eluvial–illuvial processes to promote postdepositional Ca redistribution and concentration, sand-rich

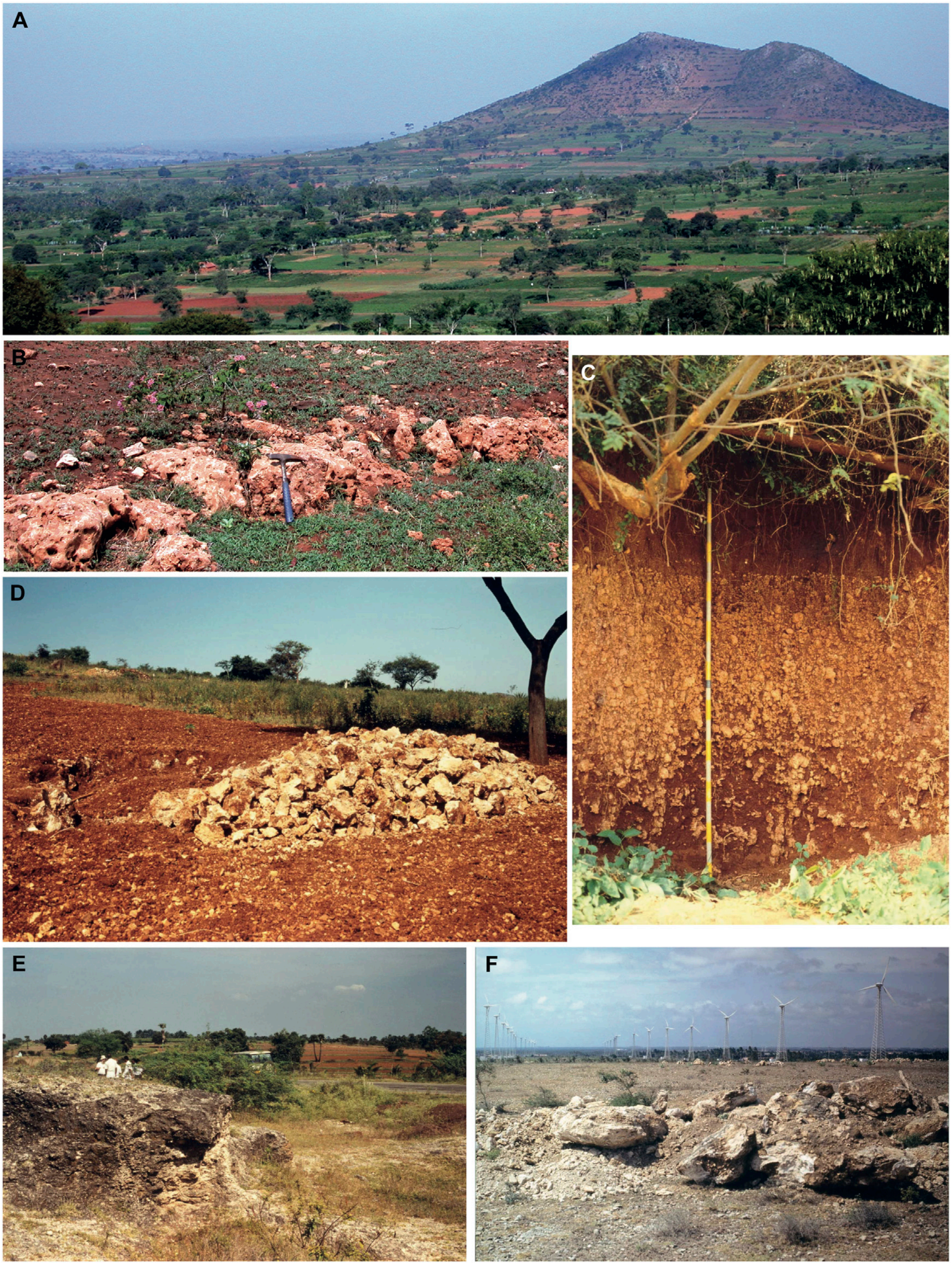

FIGURE 9 | A chromic Luvisol land system ("rhodic Paleustalf"), here on the southern Mysore Plateau near Gundlupet. **(A)** Pediment landscape on gneiss; inselberg in Ca-rich metamorphic rock (amphibolite). **(B)** Massive calcrete outcrop in a field. **(C)** Shallow calcrete hardpan ("rhodic Paleustalf, petrocalcic")—an impediment to ploughing, and extracted here because of its economic value. U–Th-dated calcrete nodules in this area were formed ca. 200 ka, i.e., during MIS 7. **(D)** Nodular B_{Ca} horizon at the wetting front. Soil profile corresponds to GU01 in **Table 1**. Here the red Luvisol contains smectite and illite (Bourgeon, 1992; Bétard et al., 2009), and is in equilibrium with the modern semi-arid climatic conditions, unlike the relict kaolinite-rich laterites shown in **Figures 4A–C**. **(E)** Calcrete plateau

(*Continued*)

FIGURE 9 | (caprock in foreground) in western Kongunad, Tamil Nadu, amid chromic Luvisols in background. Soil profiles from that area correspond to profiles SING2 and SING3 in **Table 1**. **(F)** View of another calcrete-capped plateau extending between 400 and 450 m in western Kongunad, with quarried boulders of calcrete in foreground. Here the calcrete is hard, dense, and unamenable to fragmentation other than by blasting. Photograph credits: **(A)**: N. Durand, **(B–F)**: Y. Gunnell.

in-channel deposits undergo more frequent alternations of sedimentation and erosion, with limited opportunities for pedogenesis. As a result, the former tend to be calcareous, while the latter are not.

South of the Kaveri delta, along the shores of the Palk Strait, elongated patches and ribbons of calcareous Vertisols (black map units in **Figure 5**) distinctly straddle drainage divides *between* the modern coastal river catchments, thereby occupying an elevated position in the landscape instead of lining valley floodplains as seen elsewhere. It can be inferred that these expanses of Vertisol cap older floodplain sediments that have since been incised by the modern channel systems. They presumably correspond to older—Pleistocene or early Holocene—floodplain deposits, effectively defining an older generation of alluvial terrace never until now identified or characterised as such in the geological literature.

The extensive occurrence of younger valley soils outlined by finely dendritic networks (yellow in **Figure 5**), usually highlighting low-order, plains-fed intermittent streams, classify as Inceptisols. These widespread floodplain soils are always calcareous all over the study area, particularly on Precambrian basement in Tamil Nadu and Andhra Pradesh, but conspicuously not so on the Mysore Plateau (see **Figure 5**). This Mysore Plateau anomaly is further analysed in a later section. On the Deccan basalts, these immature Inceptisols tend to be confined to low-order streams in upper catchment areas, while Vertisols otherwise prevail in wider valleys situated downstream of major river junctions (black in **Figure 5**).

Quantitative data were also available in Tamil Nadu for mapping contrasting values of soil calcareousness, a useful exploration tool for detecting the intensity of $CaCO_3$ sequestration on a regional scale. The map unit shapes in **Figure 8** suggest extensive patches of strongly to moderately calcareous soils 1) over western Kongunad and 2) along the shores of the Palk Strait. They suggest two classes of landform, both poorly investigated until now: a shallow palaeolake in the case of Kongunad—also hypothesised as such by Subramanian and Muraleedharan (1985)—and large fluvial fan-deltas extending into the Palk Strait—reported by Prabakaran and Anbarasu (2010).

Immature Non-Calcareous Soils on Valley Floors

The main distinguishing factor among deep Vertisols on valley floors in southern India is calcareousness. As a rule, within the broad valleys of the Deccan flood basalts, calcareous Vertisols line the active floodplains (see dendritic patterns displayed in black in **Figure 5**), whereas non-calcareous Vertisols extend across what we interpret as an older Quaternary fluvial terrace system, which formed broader floodways in its time (displayed in black in **Figure 6** as wider, non-dendritic ribbons of Vertisol). Contrary to what was observed on the floodplains of Tamil Nadu which lie closer to marine base level (see **Figures 1**, **8**), the contrasting pattern of calcareous and non-calcareous Vertisols in these basaltic uplands remote from sea level would suggest a cascade of Ca recycling, with decalcification of the older alluvial terraces and downward migration of geochemical barriers to calcium as river incision drives hillslope response and landscape change.

In addition to this distinction, climatic contrasts also exist across the Deccan flood basalt province between:

(i) larger valleys hosting “allogenic” streams (Jain and Tandon, 2003)—i.e., monsoon-fed perennial rivers that rise in the humid Western Ghats and flow towards the more arid interior (**Figure 1**), and where calcareous Vertisols are inset in non-calcareous (and thus, presumably, decalcified) Vertisols;
(ii) smaller valleys hosting “endogenic” streams—i.e., shorter streams rising within the dry interior and thus experiencing only seasonal flow, where calcareous Inceptisols lining tributary valleys are inset within larger map units of calcareous Vertisols. In this arid interior part of Maharashtra, Ca is clearly less mobile that farther west where monsoon encroachment occurs, and $CaCO_3$ accordingly pervades the entire depositional landscape (**Figures 5**, **6**).

To conclude on the distribution of colluvial and cumulic soils, mapping and analysing the relative positions in the landscape of 1) calcareous Inceptisols, Aridisols and Vertisols (**Figures 5**, **7**), and of 2) non-calcareous Entisols, Inceptisols and Vertisols (**Figures 6**, **7**) has provided an opportunity for ranking the depositional units of regolith hosting these soils in terms of their relative age and hypothetical origin. This enhances possibilities for identifying subtle pedogeomorphic features in the low-relief and highly engineered agricultural landscapes of southern India, with potential for future sedimentological, archaeological and/or mineral exploration. Such features include, for example:

(i) abandoned Quaternary alluvial terraces at slightly higher elevations than the currently active floodways of intermittent streams. Some occur today as residual deposits straddling modern drainage divides, such as around the Palk Strait in SE Tamil Nadu (**Figure 5**);
(ii) abandoned palaeochannels in Quaternary delta or fan-like distributive fluvial systems along the eastern seaboard of the subcontinent, Tamil Nadu in particular (**Figures 5**, **8**).

The overview also highlights that Inceptisol occurrences in southern India often belong to the "vertic" subgroup; this indicates that, although falling short of being fully categorised as Vertisols by Soil Taxonomy standards, these younger soils are smectite-rich and regionally consistent with the semi-arid conditions.

Mature Residual Soils on Pediments

Here we focus on the large expanses of upland soils left blank in **Figure 2**, i.e., soils that occur on wash pediments and hillslopes displaying slope angles of less that 5°–7°, and which extend topographically above the low-lying belts or networks of colluvial and cumulic soils previously described and mapped in **Figures 2**, **5**, **6**, **8**. Wherever annual rainfall does not exceed ~900 mm, the majority of soils associated with these landforms are red to reddish-brown (**Figure 9**), and neither kaolinitic nor calcareous. They classify as Alfisols (Soil Taxonomy), and more specifically as "chromic Luvisols" in the WRB lexicon. The diagnostic horizon of these Alfisols is "argillic," i.e., clay-rich (Bourgeon, 1994). Calcic variants of the Luvisols nonetheless also occur in a documented number of small catchments. This Alfisol variant classifies as "typic Rhodustalfs" and "rhodic Paleustalfs" (**Table 1**, and **Supplementary Material S1**). In Soil Taxonomy, a Paleustalf is defined by the presence of a "petrocalcic" horizon—a diagnostic feature highlighted in **Table 1** by Ca values exceeding 8 cmol(+)·kg^{-1} of fine earth—down to depths of 1.5 m below the land surface. Whether $CaCO_3$-rich (petrocalcic) or not (argillic), those two variants of intensely red Luvisols (**Figure 9**) are invariably hosted by weathered silicate rocks (chiefly gneiss) rather by carbonate rocks, albeit with contributions from Ca-rich minor intrusions in the Precambrian gneiss (see details in **Supplementary Material S4**). Unlike the Lixisols ("Kandiustalfs") of the Mysore Plateau examined earlier, the red Luvisols contain high-activity clays (smectite, illite), which are in equilibrium with the currently prevailing semi-arid conditions (Bourgeon, 1992; Gunnell and Bourgeon, 1997; Bétard et al., 2009). **Table 1** provides further analytical characteristics of these $CaCO_3$-rich red pedons. **Figures 9A–D** illustrates the occurrence of such soils in landscape context, here focusing on sites corresponding to profiles GU01 and T01 reported in **Table 1**.

The $CaCO_3$-rich ("petrocalcic") Luvisols on pediments are qualitatively important because they host occurrences of massive calcrete, often of economic value (see **Supplementary Material S3**). Our field surveys have so far identified four lithic calcrete occurrences (see stars in **Figures 2**, **3** for location). **Figures 9E, F** illustrates occurrences of lithic calcrete, so massive that it forms inverted topography in the vicinity of where profiles SING2 and SING3 occur (analytical results in **Table 1**).

The Mysore Plateau Anomaly

Whether residual, colluvial or alluvial, soils on the Mysore Plateau stand out as being conspicuously non-calcareous (**Figure 6**)—excepting the conspicuous petrocalcic Luvisols in the area located in **Figure 3** (star no. 3), illustrated in **Figures 9A–D**, and further detailed in the **Supplementary Material**. This absence of calcareous accumulations concerns the upper Kaveri, Ponnaiyar, Palar and Penner drainage basins (**Figure 1**), where these non-calcareous soils lining valley floors and pediment footslopes classify as immature soils: Inceptisols and Entisols at order level ("Ustropepts" and "Ustifluvents" at suborder level). Most are clay-rich, and some display vertic properties. Substituting space for time, this suggests that these young soils may be precursors to the more mature Vertisols found in most valleys outside the Mysore Plateau (compare **Figures 5**, **6**), but that drainage dynamics, analysed below, are setting the Mysore Plateau apart from trends and patterns observed elsewhere.

The primary feature of the Mysore Plateau is the broad, residual island of kaolinitic Lixisols ("Kandiustalfs") displayed as red patterns in **Figure 2**, hosting >30-m-thick kaolinitic weathering profiles and straddling a major regional drainage divide striking E–W, i.e., almost perpendicular to the Western Ghats continental drainage divide (**Figure 1**). Not only is it impossible to derive Ca from geochemically depleted Lixisols, but the Mysore Plateau is currently also undergoing intense fluvial incision and gullying around the headwaters hosting the Lixisols (**Figure 4E**). We therefore attribute the non-calcareous nature of valley Inceptisols and Entisols on the Mysore Plateau to the Quaternary drainage integration process that is still occurring across the plateau, thereby activating hillslope erosion and colluvial supply to channel systems and denying the opportunity for illuvial–eluvial processes on the valley floors to promote soil profile differentiation and Ca accumulation. In full contrast to the Mysore Plateau, non-calcareous valley soils are entirely absent in the lowlands of Tamil Nadu (**Figure 6**), i.e., seaward of the Eastern Ghats escarpment (**Figure 1**) where rivers follow gentle gradients to the sea, and where $CaCO_3$ accumulation on valley floors—valid for all stream orders—is widespread (**Figure 8**; see also **Supplementary Material S2**).

The relict occurrences of kaolinite-rich regolith along the E–W drainage divide on the Mysore Plateau still endure (**Figure 2**) because the fluvial incision is geologically very recent. Fluvial channel incision is thus currently focusing at, and inboard of, the Eastern Ghats escarpment (**Figure 1**), where the lower Kaveri, Ponnaiyar and Palar rivers are cutting and expanding headward via their respective bedrock gorges along a belt of active channel knickzones (**Figures 1**, **2**, **5**, **6**; Kale et al., 2014; Mandal et al., 2016). Stream erosion is active not just along this escarpment "fall line" but also at the valley heads along the drainage divide around Bengaluru (**Figure 1**), where ironstone-capped mesas of the Lixisol terrain are undergoing intense erosion (note ridge-and-ravine topography in **Figure 4E**, and depositional evidence, in the gravel stratigraphy of **Figure 4D**, of geologically recent erosion of the ironstone scarp).

We conclude that the dividing line among valley soils between their calcareous (in Tamil Nadu) and non-calcareous (on the Mysore Plateau) character (**Figure 6**) is approximately defined by the current position of bedrock

TABLE 1 | Analytical characteristics of calcareous red-soil pedons on pediments in semi-arid peninsular India.

Depth (cm)	**pH H_2O**	**Org. C (%)**	**Clay (%)**	**Exchangeable bases**				**CEC**[a]	
				Ca	**Mg**	**K**	**Na**		
				[cmol(+)·kg^{-1}]				**(1)**	**(2)**
Patancheru (crops)—17°35′N, 78°17′E—Andhra Pradesh—Udic Rhodustalf (Lal et al., 1994)									
0–10	6.5	0.84	17.9	5.8	1.9	0.3	0.1	8.1	45
10–20	6.5	0.79	18.4	5.6	2.1	0.3	0.2	8.4	46
20–30	6.7	0.85	32.5	10.8	2.9	0.2	0.2	14.6	45
30–49	6.7	0.85	34.5	11.0	3.1	0.2	0.2	15.1	44
49–102	7.8	0.48	39.5	14.3	3.4	0.2	0.3	17.0	43
102–145	7.0	0.23	24.3	18.9	4.7	0.2	0.4	22.2	91
Kottapalle Tanda (crops)—14°07′N, 78°16′E—Andhra Pradesh—Rhodic Paleustalf (Reddy et al., 1996)									
0–11	7.1	0.28	7.2	2.4	1.0	0.1	0.0	5.70	79
11–30	6.5	0.61	37.9	11.3	3.4	0.2	0.1	22.50	59
30–63	6.5	0.39	33.3	10.1	3.1	0.2	0.1	20.10	60
63–96	6.3	0.23	22.1	8.8	4.7	0.3	0.2	20.00	90
Manesamudram (crops)—13°53′N, 77°31′E—Andhra Pradesh—Typic Rhodustalf (Reddy et al., 1996)									
0–11	5.9	0.23	9.6	1.1	1.7	0.1	0.0	5.20	54
11–26	5.7	0.31	27.0	4.4	3.3	0.1	0.1	13.70	50
26–50	6.7	0.32	43.8	8.7	4.6	0.2	0.2	20.00	46
50–66	7.1	0.25	42.6	12.2	5.6	0.2	0.3	25.00	59
GU01 (crops)—11°47′N, 76°38′E—Karnataka—Rhodic Paleustalf—*Sol fersiallitique* (Bourgeon, 1992)									
0–10	6.9	0.84	16.4	3.4	1.8	0.3	0.0	6.1	37
10–70	6.6	0.64	32.3	7.0	3.0	0.1	0.1	10.3	32
70–100	6.8	0.58	33.3	11.7	4.1	0.2	0.2	15.0	45
100–115	7.1		19.7	11.3	4.5	0.2	0.1	18.3	93
115–150	8.3		7.5	10.5	3.9	0.1	0.3	14.4	192
Rayalpadu (crops)—13°00′N, 78°24′E—Karnataka—Rhodic Paleustalf (Lal et al., 1994)									
0–13	5.8	0.20	12.3	1.7	1.4	0.1	0.1	7.5	61
13–42	5.8	0.30	49.2	8.7	3.7	0.2	0.2	15.9	32
42–60	5.5	0.30	42.3	10.2	3.0	0.1	0.2	14.7	35
60–92	5.8	0.50	26.2	8.3	3.0	0.1	0.2	14.6	55
Yellampalli (crops)—13°45′N, 77°50′E—Karnataka—Typic Rhodustalf (Shiva Prasad et al., 1998)									
0–15	7.4	0.45	14.9	7.2	2.1	0.8	0.1	7.7	52
15–42	6.9	0.25	28.6	8.6	1.9	0.6	0.1	8.8	31
42–70	7.4	0.17	26.5	8.4	1.1	0.6	0.2	8.3	31
70–90	8.3	0.07	25.7	28.2	0.9	1.9	0.3	9.4	37
Chetra (crops)—14°42′N, 75°31′E—Karnataka—Typic Rhodustalf (Shiva Prasad et al., 1998)									
0–12	6.7	0.36	9.8	3.4	1.4	0.4	0.3	6.2	63
12–51	7.3	0.68	48.1	12.0	4.3	1.1	0.3	18.2	38
51–78	7.5	0.36	37.7	11.2	4.1	1.1	0.3	15.9	42
78–98	7.4	0.25	26.8	13.8	3.5	0.8	0.7	14.8	55
T01 (forest)—11°46′N, 76°33′E—Karnataka—Typic Paleustalf—*Sol fersiallitique* (Bourgeon, 1989)									
0–20	5.61	1.51	23.8	9.1	2.6	0.0	0.3	13.3	56
20–50	5.76	1.26	63.3	13.0	6.4	0.3	0.3	24.4	38
50–80	6.04	0.55	46.7	18.6	7.1	0.6	0.3	25.3	54
80–100	6.17	0.43	17.9	34.0	12.9	0.5	0.3	32.1	179
SHIGG1 (crops)—15°04′N, 75°26′E—Karnataka—Typic Ustropept—*Sol fersiallitique appauvri* (Bourgeon, 1989)									
0–18	7.96	0.86	15.2	11.7	1.3	0.0	0.5	10.1	66
25–50	7.34	0.62	42.5	29.7	5.0	1.5	0.5	26.6	63
50–70	7.88	0.15	18.8	30.3	5.5	0.0	0.2	24.9	132
SING2 (crops)—10°47′N, 76°58′E—Tamil Nadu—*Sol fersiallitique* (Bourgeon, 1992)									
0–15	6.4	0.31	6.3	2.6	0.9	0.2	0.1	4.2	67
15–30	6.7		20.7	8.8	2.6	0.2	0.1	12.1	58
50	7.2		5.8	4.1	0.9	0.1	0.0	5.0	86
100	8.0		11.7	16.0	1.4	0.2	0.0	10.9	93

(Continued on following page)

TABLE 1 | (*Continued*) Analytical characteristics of calcareous red-soil pedons on pediments in semi-arid peninsular India.

Depth (cm)	pH H_2O	Org. C (%)	Clay (%)	Exchangeable bases				CEC[a]	
				Ca	Mg	K	Na		
				[cmol(+)·kg^{-1}]				(1)	(2)
SING3 (crops)—10°47′N, 76°58′E—Tamil Nadu—Rhodic Paleustalf—*Sol fersiallitique* (Bourgeon, 1992)									
0–25	7.1	No data	12.3	6.6	1.1	0.2	0.9	6.7	101
25–70	7.0		32.6	13.5	2.9	0.3	0.4	17.4	98
90	8.2		21.5	40.0	2.7	0.3	0.1	18.4	271
120	8.3		6.7	30.0	1.6	0.2	0.2	10.2	340
140	8.7		1.1	8.3	0.4	0.0	0.1	3.5	421
Palathurai (crops)—10°55′N, 77°00′E—Tamil Nadu—Typic Haplustalf (Murthy et al., 1982)									
0–12	8.4	No data	13.5	11.8	0.6	0.2	0.3	13	96
12–39	8.3		20.9	17.2	1.6	0.2	0.3	23.6	113
39–57	8.6		22.9	18.8	1.8	0.2	0.3	25.2	110
57–68	8.8		21.5	17.2	1.5	0.1	0.5	25.1	117

Names are based on Soil Taxonomy and the French classification, in line with the respective data sources. Depending on $CaCO_3$ content, the soil types translate to "chromic" and "calcic" Luvisols in the WRB.

[a] *Cation Exchange Capacity measured using NH_4O acetate at pH 7, given (1) in cmol(+)/kg of fine earth and (2) in cmol(+)/kg of clay.*

knickzones on stream channels as they descend the Eastern Ghats escarpment. Drainage integration expanding from the east has not yet fully rejuvenated the landscape and fully stripped the relict kaolinite-rich regolith of the Mysore Plateau. The non-calcareous nature of valley soils on the Mysore Plateau is an important diagnostic key feature of the overall hydrological drawdown being exerted on the southern Karnataka upland by "aggressor" streams ca. 500 m above the base-level plains of Andhra Pradesh and Tamil Nadu.

REGOLITH DISTRIBUTION, AGE, ORIGIN AND DYNAMICS IN SOUTHERN INDIA: A DISCUSSION

The low-resolution but systematic maps crafted for this study from information provided by soil maps indicate that regolith in the semi-arid cratonic interior of southern India is thin but diverse and extensive. Soil maps such as these gain from being part of the toolbox of geoscientists who engage in regolith and Quaternary reconnaissance mapping in regions where scarce coverage exists otherwise. The information extracted from them constitutes a basis for conducting field inspections, for framing sampling strategies, for designing future research programmes in geoscience, and for investigating land use by historic and prehistoric societies.

Below we expand the scope of these survey-driven regolith maps by articulating the information they contain with previously published, report-based findings about late Cenozoic landscape evolution in southern India. Scope for enrichment includes direct and indirect age constraints on some regolith units, including palaeoenvironmental information and the estimation of regolith residence times. Given the widespread and intense calcareousness of soils across southern India (**Figures 2**, **8**), we also elaborate on the carbon sequestration potential of soils in the seasonally dry Tropics through silicate weathering and the precipitation of calcite—emphasizing how, as carbon sinks, the widespread calcareous soils of peninsular India make a contribution to Earth's geological thermostat (e.g., Hilton and West, 2020; Brantley et al., 2023).

Age Constraints on the Regolith of Southern India, and Correlation With Past Climates

Clues From the Kaolinite-Rich Regolith

Kaolinitic soils in southern India are fully displayed in **Figure 10**, here also—in contrast to **Figure 2**—showing areas where the current climate is compatible with ongoing formation of kaolinite-rich Ferralsols and Acrisols (WRB lexicon). The latter occur chiefly in the monsoon-drenched Western Ghats and adjacent coastal belt, not analysed here but illustrated for context. Along the east coast, a succession of dissected low plateaus consisting of Cenozoic red beds display an array of soils rich in iron and kaolinite, with "kandic" and "oxic" diagnostic horizons and varyingly classified by Soil Taxonomy as "oxic Ustropepts," "kandic Rhodustalfs," "kandic Paleustalfs," and "kanhaplic Haplustalfs" (see **Supplementary Material S1** for definitions). Despite the difficulty of translating soil types from the confusingly broad Alfisol order to WRB equivalents among Luvisols and Lixisols, these taxa are united overall by a common denominator: they define regolith which is 1) rich in iron, silica and low-activity clays, reflecting the admixture of ingredients typically found in detrital red beds sourced by eroding lateritic profiles in the hinterland such as the area circled in red in **Figure 2**; 2) strongly depleted in exchangeable bases; and 3) currently residing in a climate along the east coast of India with a nine-month-long annual dry season. The depositional sequences hosting those soils are often sealed and cemented by some form of ironstone caprock.

Although previously reported by pedologists and geomorphologists at various locations (Brunner, 1968;

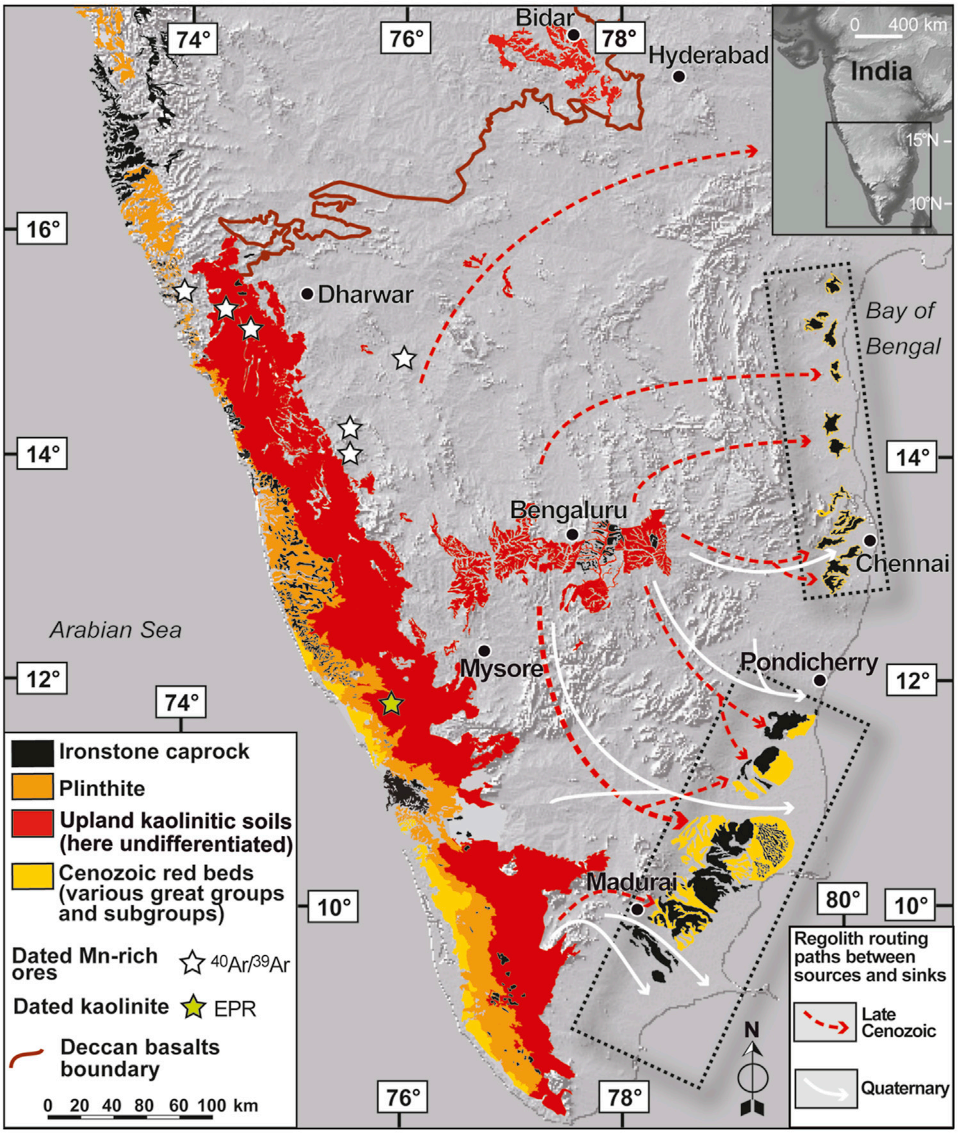

FIGURE 10 | Kaolinitic soils in southern India. Based on Challa et al. (1995), Harindranath (1999), Krishnan et al. (1996), Natarajan et al. (1997), Reddy et al. (1996), Shiva Prasad et al. (1998), with additional material for SW Maharashtra from Widdowson (1997). Indurations are also indicated: Soil Taxonomy defines "plinthite" as an iron-rich mixture of clay with quartz and other highly weathered minerals, which irreversibly hardens upon exposure to repeated wetting and drying, especially if exposed to heat from the sun. Here, extensive plateaux of thick lateritic duricrust capping thosee plinthite levels are additionally indicated as lateritic mesas, even though the distinction between laterite—a word used by geologists for over 200 years to describe a wide range of ironstone-like occurrences—and plinthite—a more restrictive concept adopted much more recently by soil scientists—is debatable on a case-by-case basis. Cenozoic flowpaths between Deccan sources and eastern lowland sinks (red arrows) are indicative. Quaternary sediment provides the host material for Vertisols, Inceptisols and Entisols occurring in the vicinity of the white arrowheads and mapped in **Figures 5**, **6**.

Brunner, 1969; Brunner, 1970; Rengasamy et al., 1978; Bourgeon, 1989; Gunnell, 1998; Bourgeon, 2001), none of the kaolinite-rich soil and regolith occurrences mapped in **Figure 2** and illustrated in **Figure 4**, now evolving under semi-arid conditions, have been directly dated. However, an indirect record of the chronology of intense weathering conditions required for generating those soil units in the past has now been obtained. Bonnet et al. (2016) and Jean et al. (2019) dated weathered manganese and ferromanganese ores capping narrow, elevated outcrops of Precambrian greenstone not documented by the soil maps (site locations in **Figure 10**; see also Sethumadhav et al., 2010). These ^{40}Ar/^{39}Ar ages from central Karnataka indicate that intense kaolinitic weathering occurred across southern India during at least two globally recognised "hothouse" intervals of the Cenozoic: 53–44 Ma (Paleocene–Eocene Climatic Optimum,

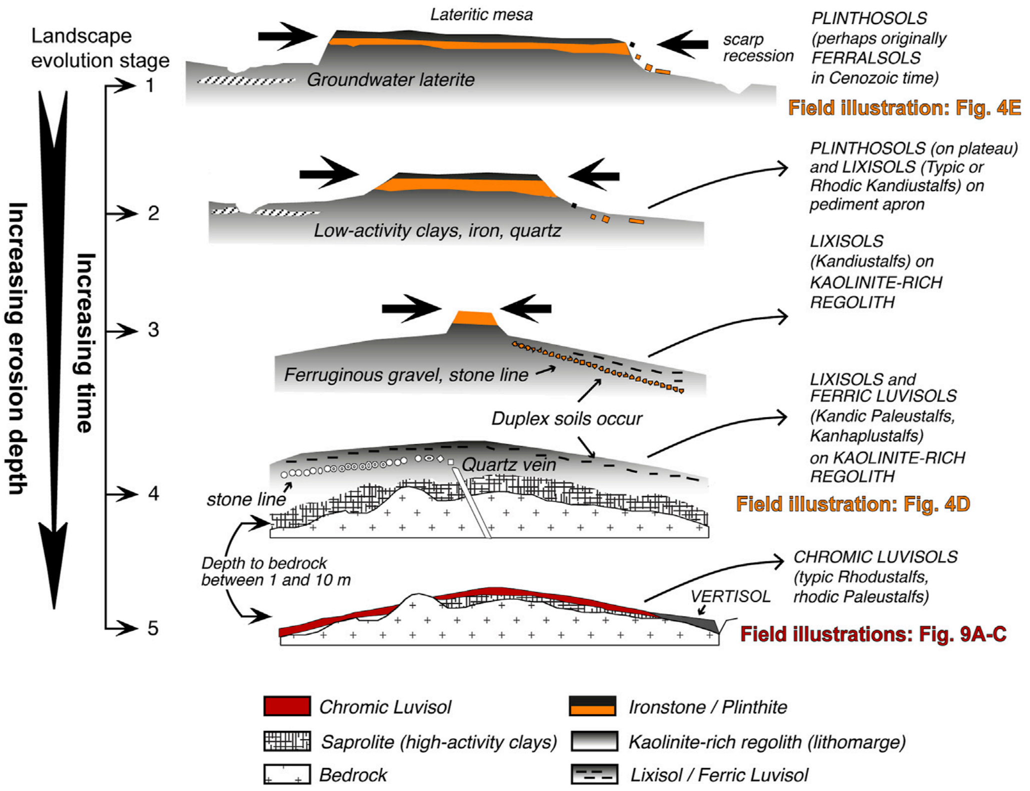

FIGURE 11 | Landscape evolution scenario for the Mysore Plateau. Five classes of soil landscape, numbered 1 to 5, currently coexist on this upland. Their relative spatial distribution is a function of denudation depth and distance from major drainage divides, but they can also be assembled into an evolutionary sequence through geological time. In 3 and 4, note the spread of ferricrete gravel across the wash pediment, which regularly occurs in the absence identifiable source areas such as a laterite-capped mesa. Such duplex soil profiles involving an erosional disconformity and displaying various kinds of "stone lines," as illustrated in **Figure 4D**, typically suggest proximity to lateritic landforms—now fully eroded—in the past. The stratigraphy of these duplex soils is not uncommonly associated with occurrences of prehistoric tools, either discarded *in situ* or transported over short distances by sheetwash processes. Landscape state (or stage) 5 (chromic Luvisols) is the most widespread on Precambrian outcrops of the Mysore Plateau and corresponds to grey areas in **Figure 2**. Cross-reference to photographs provides supporting field evidence.

or PECO), and 39–22 Ma (Late Oligocene Warming Period, or LOWP). Another peak of laterite formation was recorded during the Mid-Miocene Climatic Optimum (MMCO: 14–9 Ma). It is likely, therefore, that the kaolinite-rich regolith enclaves (from Mysore to Bidar, **Figure 10**) hosting the relict Lixisols of the semi-arid interior are a legacy of these Cenozoic hothouse conditions.

Kaolinitic weathering continues to this day in the Western Ghats (**Figure 10**), where modern rainfall totals are still high, and Mathian et al. (2019) have dated late Pliocene/early Pleistocene kaolinite crystals using electron paramagnetic resonance (EPR) spectroscopy in weathering profiles of the evergreen forest zone (sampling location in **Figure 10**). By Pliocene time, however, humid conditions were no longer occurring across the plateau interior (Jean et al., 2019). By at least late Miocene time, the Western Ghats escarpment was thus forming an effective and stable rainfall barrier to the SW monsoon (Gunnell et al., 2003). The rainshadow has since maintained itself, enhancing aridity over the Deccan and establishing the currently observed, climate-controlled weathering and soil gradient between the humid Ghats and the arid interior (Gunnell, 2000). The largest enclave of kaolinite-rich Lixisols (**Figure 2**, red circle) is thus a legacy of this wetter Cenozoic period, and is currently undergoing landscape-scale stripping along the Mysore Plateau drainage divide (see **Figure 1**) according to a landscape evolution scenario illustrated in **Figure 11**. In a nutshell, chromic Luvisols containing high-activity clays derived from primary minerals in the shallow saprolite are progressively replacing the relict Cenozoic regolith populated by low-activity clays. The rate at which this substitution is occurring is poorly documented and would require age constraints on the relict kaolinitic materials. Gunnell et al. (2007) obtained tentative land surface denudation values of ~16 mm/ka on the Mysore Plateau based on ^{10}Be concentrations in vertical quartz veins preserved in a chromic Luvisol and in a Ferralsol profile, respectively, but more extensive work would be required to gain a regionally accurate picture.

Iron- and kaolinite-rich debris from the Cenozoic soil cover eroding off the Mysore and Deccan plateaus (local-scale processes illustrated in **Figure 11**, regional extent shown by red arrows in **Figure 10**) were transported by the major east-flowing rivers and deposited on the eastern plains by avulsive fluvial systems (note the fan shapes of some orange and black outcrops in **Figure 10**). Given the abundance of quartz, hematite and kaolinite—all highly stable minerals in Earth surface environments—among its soil constituents, the resulting coastal belt of clastic red beds shown in **Figure 10** (dashed rectangles) has itself undergone post-depositional pedogenesis, with induration processes leading to prominent topographic inversions in the lowland landscape.

Clues From the Non-Kaolinitic Alluvial Sequences

Across the study area, Vertisol-covered plains correspond to overbank alluvial clay deposits now abandoned by river avulsion or incision. Extrapolating from oxygen isotope ratios in sediments in the Arabian Sea, which indicate that the driest period in the study area was the Last Glacial Maximum (earliest part of Marine Isotope Stage 2, or MIS 2) and that the Holocene was on average wetter than MIS 3 and MIS 4, Kale and Rajaguru (1987), Kale et al. (2004), and Kale (2007) proposed that Deccan rivers responded systematically to global climatic forcing signals in the following way: while the larger, east-flowing Deccan rivers tended to aggrade and avulse during glacial epochs and low sea stands—thereby generating wide depositional floodplains set to host the future Vertisols highlighted in this study; these rivers tended to re-incise their floodplain deposits in response to increased stream power during interglacial epochs—thereby generating narrower floodplains inset in the previous generation of floodplain deposits and set to host the Inceptisols also surveyed in this study. Such a pattern of fluvial response to monsoon-related palaeoclimatic change overall concurs with the behaviour widely recognised among mid-latitude rivers (e.g., Vandenberghe, 2003), where fluvial incision prevailed during interglacials, whereas aggradation prevailed during glacial epochs.

Although Vertisols are generally understood to form within time spans as short as ~5 ka (Birkeland, 1999; Pal et al., 2012), the age of the deep Vertisols (>1 m) in the upland basin illustrated in **Figure 7** would need to be further investigated. **Figures 1**, **5**–**7** show that west-flowing rivers have encroached headward from the Western Ghats escarpment into the plateau, the "aggressor" streams having cut a deep embayment in the continental drainage divide and seemingly amputated the western portion of the extensive Vertisol outcrop interpreted earlier as a large palustrine floodbasin. Similar to processes occurring along the Mysore Plateau drainage divide, this beheading illustrates how sharply drainage integration at plateau edges can modify the soil landscape (Harbor and Gunnell, 2007; Gunnell and Harbor, 2010).

Clues From U-Series Calcrete Dating

By broad consensus, calcrete is an indicator of semi-aridity (e.g., Tandon and Kumar, 1999; Alonso-Zarza and Tanner, 2010), but is otherwise a rather blunt tool for establishing precise palaeo-rainfall brackets (Dhir et al., 2004; Sreedhar et al., 2008; Srivastava et al., 2021). Alpha petrofabrics, i.e., micromorphological features predominantly resulting from physicochemical precipitates, which are widespread on non-carbonate host rocks in southern India, are more commonly associated with drier conditions than beta petrofabrics, i.e., biogenically formed features (Tanner, 2010). However, the U–Th age distribution of carbonate accumulations on the Indian craton, which ranges from ~300 to ~18 ka (Durand et al., 2016; see **Supplementary Material S5**), does not correlate in any systematic way with notionally drier (glacial) or wetter (interglacial) epochs. Evidence, therefore, suggests overall that widespread $CaCO_3$ accumulation and retention across the land surface has been a relatively continuous process in peninsular India since at least Middle Pleistocene time. The relative insensitivity of calcrete petrofabrics to the global succession of Quaternary palaeoclimatic oscillations is ascribed here to the Western Ghats topographic barrier, which will have buffered the Deccan Plateau from changes in SW monsoon rainfall intensity and thus maintained a steady bandwidth of semi-arid conditions conducive to calcrete formation and preservation. Abundant gypsum deposits within some of the high-activity clay depocentres of Tamil Nadu (Vertisol areas in **Figures 5**, **8**), which typically host deep Vertisols (see **Supplementary Material S3**), also confirm the long-term stability of arid conditions in the drier core areas of the subcontinent.

Clues From Geoarchaeology

Southern India hosts a wealth of archaeological sites, the oldest dating to the early Pleistocene (Pappu et al., 2011). The Vertisols of the Deccan valleys in Maharashtra, in particular, have been investigated for their archaeological content. They contain abundant artifacts on the soil surface and within its deep cracks. This has suggested that the clay-rich deposits are older than the incursion of the corresponding human cultures ca. 5–4 ka, but (implicitly) younger than any of the more ancient prehistoric industries also reported from Maharashtra—vestiges of which are distinctly lacking from the region's Vertisols (Corvinus et al., 1973; Mishra, 1995). The widespread presence of Vertisols and Inceptisols on distinguishable generations of alluvial fill deposits also raises the issue of sediment sources and the causes of sediment supply to the streams. The default option would be to link major events of sediment delivery to climate change. However, given the evidence of relatively steady semi-arid climates in the rainshadow of the Western Ghats (see earlier sections), future investigations may accredit the notion that at least some generations of cumulic soil in southern India were linked instead to successive, but poorly documented, episodes of deforestation-related soil erosion during late prehistoric and pre-colonial historic time (see, e.g., Bourgeon et al., 2012; Bauer, 2013; Morrison, 2015).

Greatest stratigraphic complexity, with rich mosaics of potentially datable, artefact-rich Quaternary landforms and deposits, is encountered in transitional areas at the boundaries between the Archean craton and some of its younger cover rocks, such as:

(i) among the Proterozoic outcrops that occur along the boundary between the Deccan basalts and the craton (Kaladgi and Bhima Series, dashed rectangle in **Figure 3**), where exposures of sandstone and quartzite have released clasts to hillsides and riverbeds and thereby provided good lithic toolmaking materials (e.g., Pappu, 1984; Paddayya and Petraglia, 1995; Paddayya et al., 2002; Petraglia et al., 2003; Paddayya and Deo, 2014; Deo et al., 2022);

(ii) in the outer and inner coastal belts along the Bay of Bengal, which host several generations of alluvial deposits generated by large, avulsive rivers descending from the Deccan Plateau (Krishna, Penner, Palar, and Kaveri rivers; Resmi and Achyuthan, 2018) and from the Southern Ghats (Gardner, 1986; Brückner, 1988). This coast-parallel apron of deposits (dashed rectangles in **Figure 10**) is a composite mosaic: it consists of the late Cenozoic deposits today forming topographically inverted lateritic plateaus (orange and black map units in **Figure 10**), and younger generations of inset Quaternary fluvial fans and floodplains (mapped as Entisols and Inceptisols, with some Vertisols, in **Figures 5**, **6**), many of these highly calcareous (**Figures 2**, **8**). The resulting stratigraphy contains a variety of raw materials conveyed to these depocentres from the hinterland, mainly rolled quartz quartzite, and quartzitic sandstones, all suitable for toolmaking (Akhilesh et al., 2018).

(iii) In SE Tamil Nadu, where late Neogene and Pleistocene alluvial processes have interacted with aeolian and shifting shoreline processes—generating interfingering mosaics of gravel fans, sand dunes, and various continental, marine or palustrine clay deposits on low topographic gradients, all distributed over small increments of elevation (Gardner, 1986; Brückner, 1988). Deposits include U–Th-dated but archaeologically barren calcarenite from the last interglacial marine highstand (Idindakarai Series, 112–124 ka, MIS 5e) capped by Late Pleistocene eolianites. The topmost stratigraphic unit is the red Teri Series (extensive fluvial sands and coastal dunefields, **Figure 8**), mapped by Natarajan et al. (1997) as Arenosols. The sands host an abundance of microlithic artefacts (reviewed in Akhilesh et al., 2017), and luminescence dating indicates that dune accretion occurred between ~25 and ~11 ka (Jayangondaperumal et al., 2012), thus initially at a time of very low sea levels when the wide, gently sloping continental shelf of the Palk Strait was exposed to strong NE monsoon winds, thus provided opportunities for blowing fluvial sand from the shelf westward onto higher ground. Dune stabilisation and post-depositional sand reddening processes occurred post-15.4 ka on fluvial sands and post-11.4 ka on dune sands, but other red dunes further north, along the coast of Andhra Pradesh, were active intermittently from the last sea-level lowstand ca. 90 ka to present time (Reddy et al., 2013). Dune occupation by microlithic cultures at the time of sand-mass stabilisation by vegetation and pedogenesis during early Holocene sea-level rise is a plausible scenario, with microlithic cultures in this coastal region of Tamil Nadu perhaps roughly coeval with those reported above from the Vertisols in Maharashtra.

Importance of Terrestrial $CaCO_3$ Accumulation for Carbon Sequestration in Calcareous Soils

Whether on the Deccan flood basalts or on the South Indian craton, a key finding from the maps is the widespread distribution of calcareous soils in southern India (**Figures 2**, **5**, **8**)—far more extensive than localised calcrete occurrences previously documented by Durand et al. (2006a), Durand et al. (2006b), Durand et al. (2007), Shankar and Achyuthan (2007), or Achyuthan et al. (2012). Southern India is thus likely to host many more undocumented calcrete accumulations in the subsurface, with scope for future exploration and analysis.

This abundance of $CaCO_3$ in the soils and regolith of peninsular India illustrates the important role of secondary terrestrial carbonates not just in calcium budgets but also in the global carbon cycle via the precipitation of $CaCO_3$. Secondary carbonate acts as a sink for inorganic carbon because a significant proportion of Ca released during weathering can be trapped in regolith and hosted *in situ* for an indeterminate length of time (Harrison and Dorn, 2014; Monger et al., 2015; Dietrich et al., 2017; Dietrich et al., 2021). On the Mysore Plateau, Violette et al. (2010) estimated that up to 82% of the Ca in soil calcrete nodules was derived from local metamorphic bedrock weathering, thus leading to the consumption of an equivalent proportion of atmospheric CO_2 in the past given that silicate weathering, and ensuing terrestrial carbonate precipitation, captures more atmospheric CO_2 than in the case of carbonate weathering—which re-emits CO_2 when the solutes eventually precipitate as $CaCO_3$ in the ocean. Vertisols were also shown to constitute a favourable environment for promoting calcite formation and concomitant atmospheric CO_2 storage in soils, with pedogenic carbonate accumulation occurring within short time scales probably because of a strong confinement of pore waters—already rich in dissolved carbonates, as confirmed by high Sr, U and Mg concentrations—in Vertisols (Violette et al., 2010).

The resulting large quantities of $CaCO_3$-rich accumulations can, in turn, undergo several episodes of dissolution, releasing Ca to the geochemical cascade in the semi-arid landscape (Dietrich et al., 2021). The range of radiometric ages for calcrete summarised in **Supplementary Material S5** suggests, for example, that two nested cycles operate conjunctively in the cascade: $CaCO_3$ precipitation occurred in pulses during the Middle and Late

Pleistocene, as exemplified by the consistency of peak calcrete ages at 300 ka (end of MIS 9 interglacial) and 200 ka (end of MIS 7 interglacial); but the enduring dry climate has been essential in retaining pedogenic $CaCO_3$ concentrations in the soils and regolith rather than releasing all the calcium to the ocean. As a result, calcium is redistributed across soil catenas mostly on a local scale and is thus preserved extensively in calcareous soils across the landscape (**Figures 2**, **5**, **8**). This short-range Ca cycle is qualitatively detectable in the mineralogy and micromorphology of the different calcrete fabrics (Durand et al., 2006a; Durand et al., 2018), which display successive episodes of accretion and redistribution but little evidence of net loss through carbonate solution. Few karstic features are likewise observed in the field, whether on calcrete duricrusts or among the scarce Precambrian limestone outcrops. The solution and reprecipitation cycles are not, however, detectable in any of the U–Th age patterns—perhaps partly because, when dating impure carbonates, age precision is relatively low and decreases with increasing carbonate age (Durand et al., 2016).

In summary, since the cessation of regionally extensive, kaolinite-rich regolith-forming conditions, and thus perhaps since late Miocene time, it appears that the climate has never been humid for sufficiently long periods to fully dissolve existing secondary carbonate stocks in the regolith and to fully remove them from the landscape. Long-term geochemical budgets have favoured Ca retention, with most cumulic and colluvial soils (including young soils: Inceptisols) and some residual chromic Luvisols on pediments ensuring the bulk of carbon sequestration in southern India. As indicated in **Figure 11**, stripping the Mysore Plateau of its relict lateritic soils and exposing the saprolite to Luvisol production reboots the "surface reactivity" (*sensu* Caves Rugenstein et al., 2019) of the Indian subcontinent, accentuating CO_2 drawdown through the exposure of fluid flows to reactive primary silicate minerals (Brantley et al., 2023) rather than to the low-activity clays and iron and aluminium hydroxides prevalent in the relict Ferralsols and Plinthosols of the Archean craton and Deccan basalts.

Another soil-related ecosystem service encapsulated in **Figure 11** is that stripping the kaolinite-rich upland Lixisols and extensively substituting this relict soil cover with chromic Luvisols generates geochemically fertile tropical soils (see landscape in **Figure 9A**) containing high-activity clays (high CEC) and steady stocks of exchangeable bases (see **Table 1**). The relatively prosperous agriculture of southern India owes much to the native soil fertility of its chromic Luvisols, i.e., the class of residual soils that covers most of the unlabelled areas in **Figure 2**—particularly the Mysore Plateau, but also other parts of semi-arid Karnataka, Andhra and Tamil Nadu. Despite widespread stripping of the A horizon of these soils after many centuries of forest clearance and arable farming, geochemical fertility is nonetheless unusually high in the widely exposed B and C horizons (**Table 1**). Widespread manuring in a densely populated rural society primarily organised around mixed farming systems has helped to partly compensate for deficiencies in organic matter of the exposed B horizons. Given also the shallow weathering fronts and relatively thin saprolite (C horizon), saturated overland flow on the low-angle pediment slopes is high and has promoted widespread runoff harvesting opportunities, with thousands of water storage ponds used for surface irrigation by villagers—many of them many more than 1,000 years old (Bourgeon, 1987; Gunnell and Anupama, 2003; Shanmugasundaram et al., 2017). This has allowed wet rice cultivation on most valley Inceptisols—whether calcareous (**Figure 5**) or not (**Figure 6**)—despite the semi-arid climate.

CONCLUSION

Systematic evidence derived from survey-based soil maps in southern India points to directional climatic change in the geological past from regionally humid and laterite-forming to regionally drier conditions. Relatively steady semi-arid conditions in the rainshadow of the Western Ghats, probably persistent throughout the Quaternary, arrested the kaolinitic weathering regime still prevalent in late Cenozoic time and promoted instead widespread $CaCO_3$ accumulation and the development of calcareous soils on low-gradient hillslopes and valley floors. Given the scarcity of carbonate rocks throughout the study area, soil calcareousness is ascribed to pervasive primary weathering of the Precambrian silicate rocks and late Mesozoic flood basalts—a dominant feature throughout the region below the ~1,100 mm isohyet. This fact highlights the importance of Quaternary regolith in southern India as a carbon sink, with the elevated escarpment in the west acting as a major gatekeeper against SW monsoon precipitation encroaching into the Deccan plateau and promoting $CaCO_3$-dissolving conditions. It highlights how a fine balance between soil production and soil erosion in a cratonic plateau environment can also contribute to modulating Earth's geological thermostat through silicate weathering—a process not exclusively endemic to mountain environments. Natural soil fertility is also ensured by the high-activity clays and base saturation of the widespread chromic Luvisols. Their unique features militate in favour of promoting policies for long-term soil conservation in peninsular India.

This preliminary synthesis raises questions about the links, rates and lags between 1) external forcing factors such as past climate change and 2) the process of continental-scale drainage integration, which sets its own pace of erosion and soil formation across eroding landscapes. Drainage integration from the east and west, across the Eastern and Western Ghats, respectively, has upheld a dynamic pedogeomorphic regime, while the semi-arid climate has ensured long-term self-similarity of weathering intensity and soil types at order and suborder level.

The broad scenarios of Quaternary alluvial and colluvial dynamics inferred here from soil interpretation at great-group and subgroup levels set the stage for a coherent future programme of fluvial terrace dating and wider palaeoenvironmental correlation across peninsular India. Some scientifically and educationally valuable sites and sections, such as the calcrete and gypsum deposits of Kongunad (**Supplementary Material S3**) and the polygenetic regolith stratigraphy illustrated in **Figure 4A**, would also deserve attention from geoheritage gazetting bodies in a fast-developing country with a large appetite for aggregate extraction, still too weakly counteracted by regulatory measures aimed at enforcing rescue archaeology. Crucially, a record of past environmental changes, which may also document the timing and patterns of hominin, human and faunal dispersals across Eurasia, almost certainly lies buried at shallow depths of 1–10 m within the Quaternary deposits hosting the different generations of Vertisols, Entisols and Inceptisols. These should occur in the form of stone tools and perhaps fossil faunas, some of which have already been sporadically encountered in or *ex situ*—whether eroding out of the stratigraphy along topographic bluffs and in channel headwaters, preserved in abandoned riverbeds, or scattered directly across the land surface on the pediments of southern India. Systematic meso- to fine-scale mapping of Quaternary landforms and sediments at regional scale should be a major step towards documenting that record in coming years.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YG: Conceptualization, data curation, investigation, methodology, formal analysis, resources, visualization, writing—original draft, writing—review and editing. ND: Formal analysis, investigation, methodology, writing—review and editing. SP: Investigation, resources, writing—review and editing. All authors contributed to the article and approved the submitted version.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.escubed.org/articles/10.3389/esss.2024.10097/full#supplementary-material

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