The High Deccan duricrusts of India and their significance for the 'laterite' issue

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In the Deccan region of western India ferricrete duricrusts, usually described as laterites, cap some basalt summits east of the Western Ghats escarpment, basalts of the low-lying Konkan Plain to its west, as well as some sizeable isolated basalt plateaus rising from the Plain. The duricrusts are iron-cemented saprolite with vermiform hollows, but apart from that have little in common with the common descriptions of laterite. The classical laterite profile is not present. In particular there are no pisolitic concretions, no or minimal development of concretionary crust, and the pallid zone, commonly assumed to be typical of laterites, is absent. A relatively thin, non-indurated saprolite usually lies between the duricrust and fresh basalt. The duricrust resembles the classical laterite of Angadippuram in Kerala (southwestern India), but is much harder. The High Deccan duricrusts capping the basalt summits in the Western Ghats have been interpreted as residuals from a continuous (but now largely destroyed) laterite blanket that represents *in situ* transformation of the uppermost lavas, and thereby as marking the original top of the lava pile. But the unusual pattern of the duricrusts on the map and other evidence suggest instead that the duricrusts formed along a palaeoriver system, and are now in inverted relief. The two interpretations lead to different tectonic histories. Duricrust formation involved lateral material input besides vertical elemental exchange. We may have reached the stage when the very concepts of laterite and lateritization are hindering progress in regolith research.

1. Introduction

The Western Ghats (syn. Sahyadri Range) of India constitute a great escarpment similar to many at rifted continental margins. The nearly 1500-km-long escarpment is cut across the Late Cretaceous Deccan flood basalts in the north and Precambrian igneous and metamorphic rocks in the south (figure 1a) (Ollier and Powar 1985; Gunnell and Radhakrishna 2001; Ollier 2004). Between the Ghats and the Arabian Sea is the Konkan Plain, a footslope related to eastward retreat of the escarpment during Cenozoic time. The escarpment also forms the continental drainage divide.

Late Cretaceous to early Tertiary, 'high-level' ferricrete duricrusts cap the basalt summits east of the escarpment in the southern Deccan region, and are absent from the northern Western Ghats (roughly north of Pune, figure 1a). Many are in a long line called the Bamnoli Range. Such duricrusts also cap sizeable isolated basalt plateaus that rise from the Konkan Plain. Mid-Tertiary and younger, 'low-level' ferricretes outcrop extensively on the Konkan Plain, on the Deccan basalts and basement rocks, south of $\sim 18°$ latitude. The duricrusts result from impregnation of saprolite (rock weathered *in situ*) with iron oxides and hydroxides. They have usually been called laterites (e.g., Widdowson

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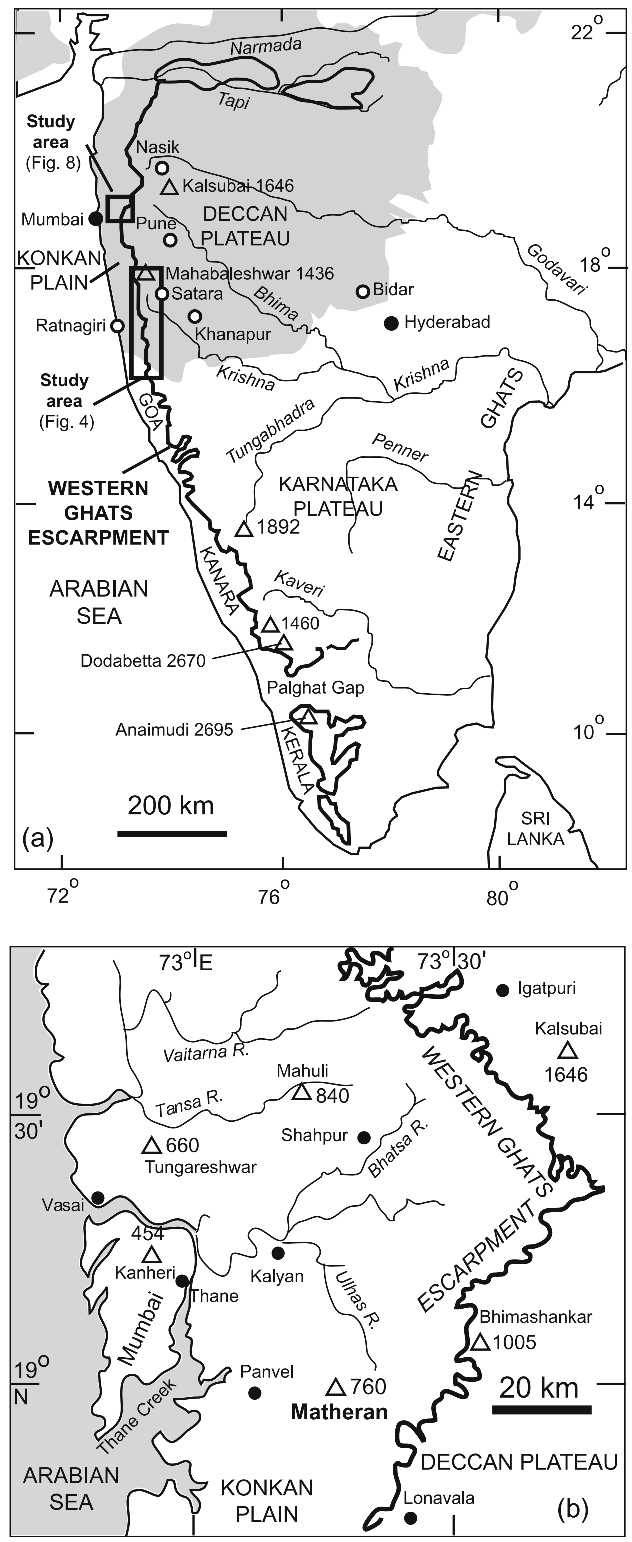

Figure 1. **(a)** Map of India showing the Western Ghats, the outcrop of the Deccan Traps (shaded), the main physiographic features, drainage lines, prominent summits (elevations in metres), and localities and geographic regions described in the text (modified from Ollier and Powar 1985). Box along the Western Ghats and box east of Mumbai are the areas of this study. **(b)** Map of the main physical features of the Konkan Plain and the Western Ghats escarpment east of Mumbai, showing the location of Matheran.

and Cox 1996; Widdowson 1997; Widdowson and Gunnell 1999).

Widdowson and Cox (1996) and Widdowson (1997) have suggested that the 'high-level' ferricrete duricrusts of the southern Deccan represent *in situ* transformation of the uppermost lava flows forming the Deccan Plateau, and mark the original top of the lava pile. We think that the duricrust distribution suggests another mode of origin (inversion of relief), and have also found a more significant problem: the duricrusts do not correspond to the 'laterite' of the literature. Our observations are relevant to the highly complex issue of laterite and laterite genesis.

2. Duricrust, laterite, and ferricrete

We first explain the terminology we are using. *Duricrust* is a general term for a hard crust formed at or near the ground surface, regardless of the composition or mode of formation. Lamplugh (1902) suggested that duricrusts could be named after the dominant cementing element, so there are calcrete, silcrete, alcrete and ferricrete duricrusts. The term *laterite* originated exactly two hundred years ago when laterite was first described from southern India (Angadippuram, Kerala) by Buchanan (1807). Laterite has since been the subject of great ambiguity and debate. Buchanan's (1807) original definition included some inaccuracies (Ollier and Rajaguru 1989). Later workers sometimes used the term for concretionary iron rich material, or for a whole profile that was assumed to have formed together (the laterite or Walther profile), and sometimes even for a red soil that may or may not have iron-rich concretions or the 'typical' laterite profile.

Perhaps the commonest view of laterite is shown in figure 2, which seems to originate with Millot (1970) and has been reproduced in countless works (e.g., Thomas 1974; Chorley *et al* 1984; Ollier 1991). The profile has several zones, which are:

- Soil
- Crust
- Mottled zone
- Pallid zone
- Weathered bedrock (saprolite)

The lateritic crust is often categorized as massive, pisolitic (or similar term meaning consisting of isolated concretions), vesicular, vermicular or vermiform (having worm-like holes), and occasionally other terms.

Local usage varies around the world. In Western Australia pisolites of ferricrete about a centimetre across are sold as laterite for use in gardens or paths. Pisolites may be cemented together to form

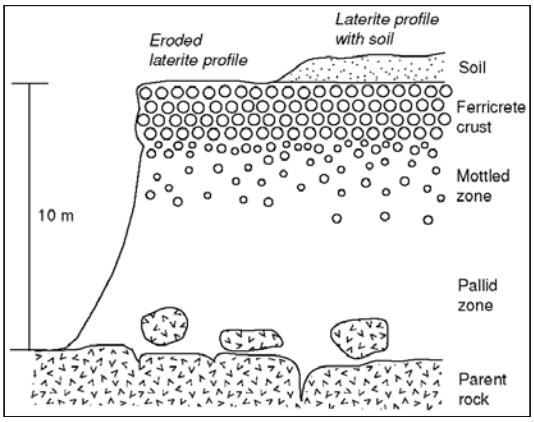

Figure 2. Typical textbook illustration of a laterite profile (e.g., Thomas 1974; Chorley *et al* 1984; Ollier 1991). Rock structure is usually preserved in the pallid and mottled zones indicating that these zones consist of weathered rock *in situ* with no volume alteration, i.e., they are saprolite.

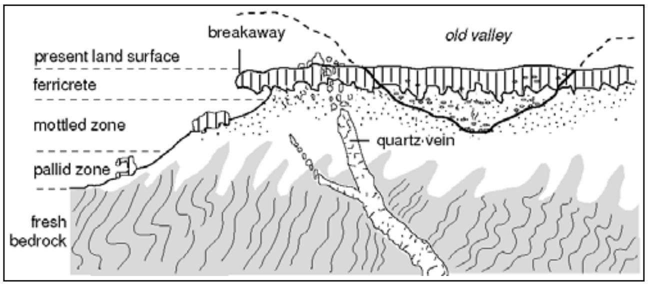

Figure 3. A simplified sketch of the Walther laterite profile from Western Australia (not to scale, Walther 1915), with translation of original German terms into English by Ollier (1995).

larger blocks or crusts. In East Africa pisolitic ferricrete is called *murram*, and widely used in road-building. In Fiji pisolitic or indurated material is largely absent, but many red soils are described as laterite. In South Australia a profile with mottled and pallid zones was regarded as 'lateritic' even though the crust was missing and presumed to be eroded (Daly *et al* 1974). Modern texts on regolith (Ollier and Pain 1996; Taylor and Eggleton 2001) almost despair at the prospect of defining laterite. Schaetzl and Anderson (2005) write: "By now it should be obvious that perhaps no other group of soils has such an ill-conceived, persistent terminology as have laterites." Because of the confusion associated with the term laterite (see also Paton and Williams 1972) there has been a tendency in recent years to use *ferricrete* instead. We find that the High Deccan duricrusts are ferricrete of a sort, but still very different from many ferricretes that were once termed laterites.

Even more controversy is associated with the origins of laterite. Early workers (e.g., Jutson 1914; Walther 1915; Woolnough 1927) inferred an autochthonous/*in situ* origin of laterite, on peneplains, due to upward movement of iron across a vertical profile, noting that the lower, pallid zone was depleted in iron (figure 2). However, Walther (1915) also seems to have recognized a role for valleys and unconformities (figure 3). It is possible to calculate the iron content in the 'laterite' crust, compare it with that of the bedrock, and work out how much bedrock is required to produce the observed thickness of crust. Calculations by Trendall (1962) on a laterite in Uganda suggested that a large amount of surface lowering was required, producing what he called 'apparent peneplains.' The frequent unconformity between ferricrete-cemented detrital material and the underlying rocks is good evidence against the origin of ferricrete by pure chemical weathering of the underlying rocks *in situ* (Ollier and Galloway 1990). But the idea of a simple genetic relationship between samples in a vertical sequence through a 'laterite profile' is still prevalent. It is most evident in the Schellmann diagrams (Schellmann 1981) that are still widely used (e.g., Borger and Widdowson 2001). Their many shortcomings and in-built assumptions have been pointed out by Bourman and Ollier (2001).

Some authors, however (e.g., Ollier and Pain 1996), have found evidence that the iron that enriches the ferricrete is derived laterally, from upslope. This removes the quantitative problems of Trendall-type calculations, and also fits some observed association with drainage lines. If the iron is derived laterally the ferricrete is not the result of simple up-or-down movements of iron along a vertical profile. This is an important consideration for our study area.

3. Field data on the High Deccan duricrusts

We have found no detailed descriptions and illustrations of the High Deccan duricrusts in the literature. Widdowson (1997) interpreted the 'laterite profiles' around Mahabaleshwar and the Bamnoli Range in the Koyna-Patan-Satara region (figures 4, 5) as formed by *in situ* breakdown of the underlying basalt lavas. He noted that preservation and exposure of the entire profiles is uncommon, but some complete sections may occur in precipitous cliffs around the margins of the mesas though access to them is notoriously difficult. We have made observations of these duricrusts at several excellent outcrop locations at the Ghats summits in the Bamnoli Range (around Koyna and Satara), on the Mahabaleshwar and Panchgani plateaus, as well as the Matheran tableland (760 m) rising prominently from the Konkan Plain, 50 km east of Mumbai (figure 1b).

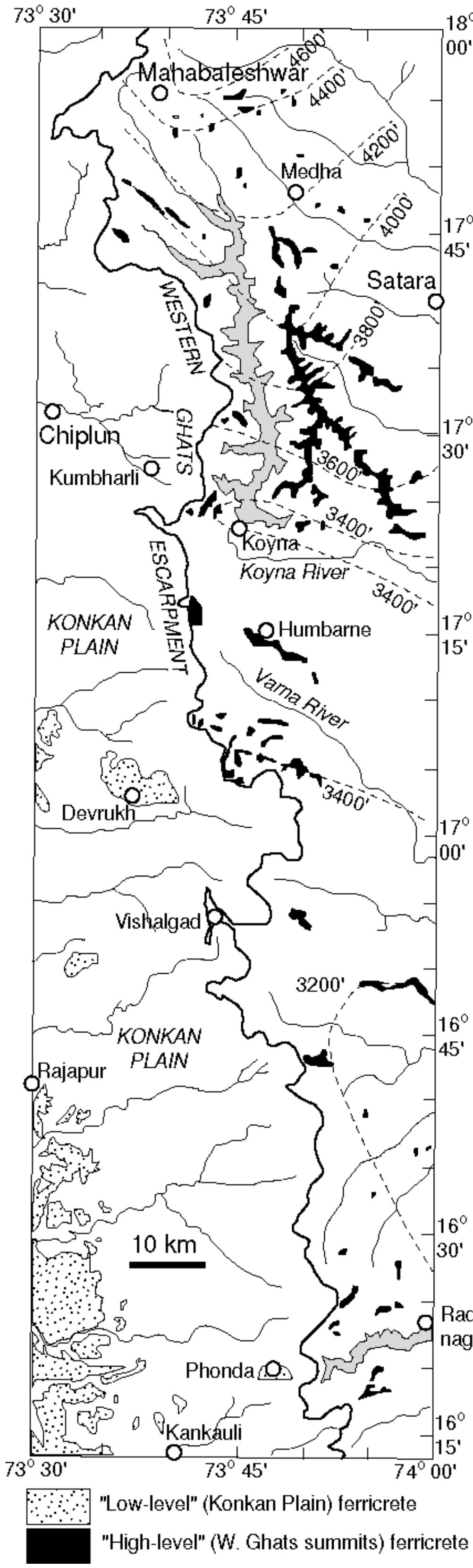

Figure 4. Map of the high-level ferricrete-capped mesas (black) east of the Western Ghats escarpment. The stippled area on the Konkan Plain shows the younger, low-level laterite. Based on Widdowson (1997). The base of the ferricrete as contoured (in feet) by Widdowson (1997) is shown by dashed lines.

3.1 *The Satara–Patan–Koyna region*

Spectacular dissected lava plateaus and mesas are seen in the Satara region, the lower of the plateaus (such as Sajjangad/Parli Fort) capped by an extensive (tens of kilometres), columnar-jointed, 'simple' flow (figure 6A). The higher mesas and buttes show the ferricretes at the summits, with the simple flow forming a distinct bench at lower elevations. From a distance it is difficult to say whether the plateaus are topped by a resistant lava flow or the ferricrete, as both are black and columnar-jointed. At close range ($\sim$100 metres), the ferricretes show white patches due to lichen growths, which the basalts do not. In hand specimen, ferricretes are black due to a thin microbial skin, and show shades of red, brown, yellow or purple when this is hammered off (figure 6B).

We observed clear contacts of the ferricrete (25 m thick) with the underlying lava flow (saprolite) on the mesa near Parambe village on the Satara-Kas Road (figure 6C, D). No mottled or pallid zone is present. The mesa at Pittri village (figure 6E), 3 km to the east, hosts a Shiva shrine in a small cave developed at the ferricrete-saprolite contact. Again, no mottled or pallid zone exists. Wherever we could observe it, the base of the duricrust was undulating in three dimensions, like an egg-board with an amplitude of about a metre. This we interpret to be a chemical front; it is by no means an unconformity or structural feature inherited from the basalt.

The Ghats summits near Bandhvad village (approachable from Kashil village, figure 5) show 15-m-thick ferricrete with holes directly overlying saprolite. To its southwest, the village of Sadavaghapur lies on an extensive summit plateau topped by ferricrete (figure 6F) which shows a weathered, highly vesicular surface and forms boulder fields. Kapadia (2003) writes that such boulder fields are common in the southern region of the Deccan Traps and known locally as *sadas*. The local name for the ferricrete is *jambha*, for purple. The whole Sadavaghapur plateau is decreasing in size by mass movements of large joint blocks of ferricrete along its edges (figure 6F). Between Sadavaghapur and Borgevadi, the roadcut shows a section of ferricrete at the top (10 m), underlain by a thick saprolite zone (45 m). The ferricrete forms an overhang or breakaway over the saprolite, with caves developed at the contact. The saprolite shows highly colourful weathering patterns, colour banding, and 'mega-mottles' (figure 6G) but no true mottled zone. The saprolite is followed downwards by fresh, columnar-jointed basalt (5 m), a red altered tuff ('bole') bed (2 m) below it, and a second, lower basalt lava flow under the red bed, at Borgevadi.

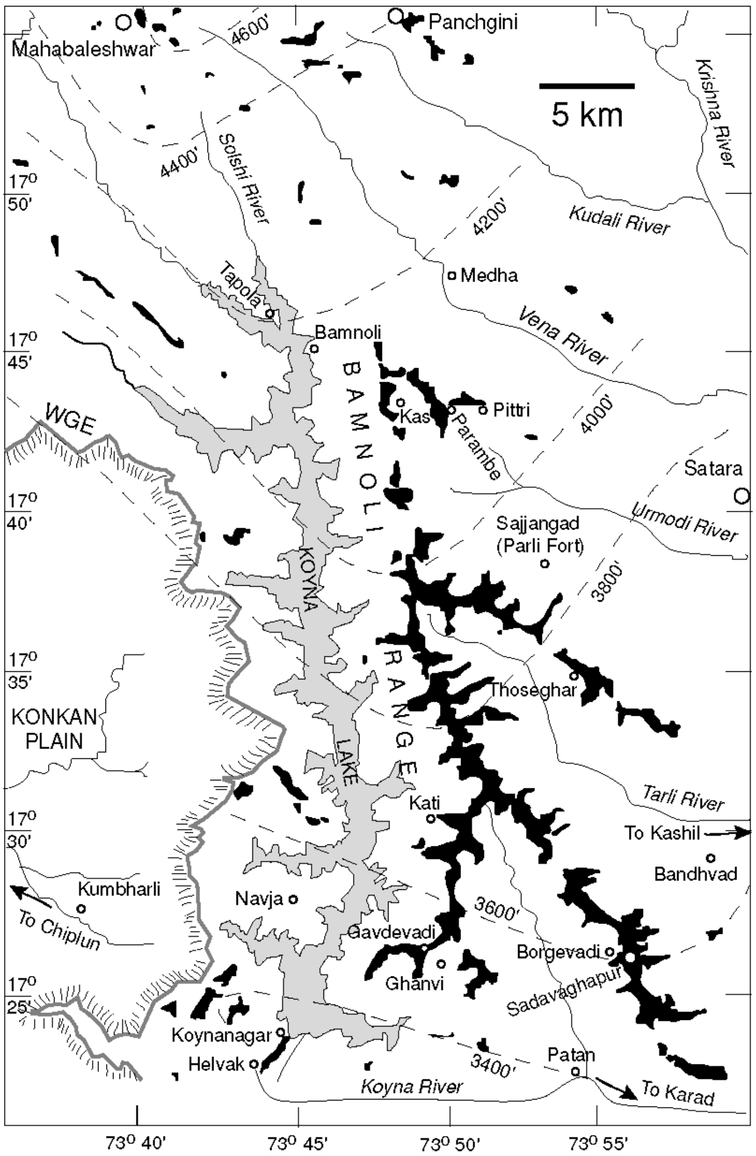

Figure 5. Details of the pattern of ferricrete-capped mesas (black) of the Bamnoli Range, modern drainage and topographic features, and towns and villages, including locations visited. Based on Widdowson (1997) and Kapadia (2003). WGE is Western Ghats escarpment. The base of the ferricrete as contoured (in feet) by Widdowson (1997) is shown by dashed lines.

At Ghanvi and Gavdevadi (figure 5, approachable from Patan), duricrust is overlain by red pebbly clay and underlain by the saprolite. In the roadcut just outside Gavdevadi, the whole basalt has been transformed into ferricrete *in situ* in such a way that even the original flow units can be observed (figure 6H). At Thoseghar, approachable from Gavdevadi or from Sajjangad, thick (20–25 m) ferricrete duricrust overlies saprolite.

At Koynanagar, at the abandoned quarry near the Koyna dam, duricrust overlies bright red clay (like a 'ferrallitic' soil) that in turn rests upon a thick basalt lava flow showing complex columnar jointing patterns. We observed no mottled or pallid zones below the duricrust.

3.2 *The Panchgani–Mahabaleshwar area*

The Panchgani tableland 20 km east of the Mahabaleshwar resort (1436 m) is a large, flat, elevated plateau 1300–1340 m above sea level, and capped by duricrust (figure 7A). The plateau here is broadly convex but ferricrete patches outcrop all over, through a centimetre-thin cover of fawn material, interpreted by Kale (2000) as a windblown deposit. It is reminiscent of loess though it has more fine sand than typical loess. It is not derived from weathering of the ferricrete.

On the western-southwestern side of Panchgani tableland, the vermiform, 25 m-thick duricrust shows some caves under it (fugure 7B) where

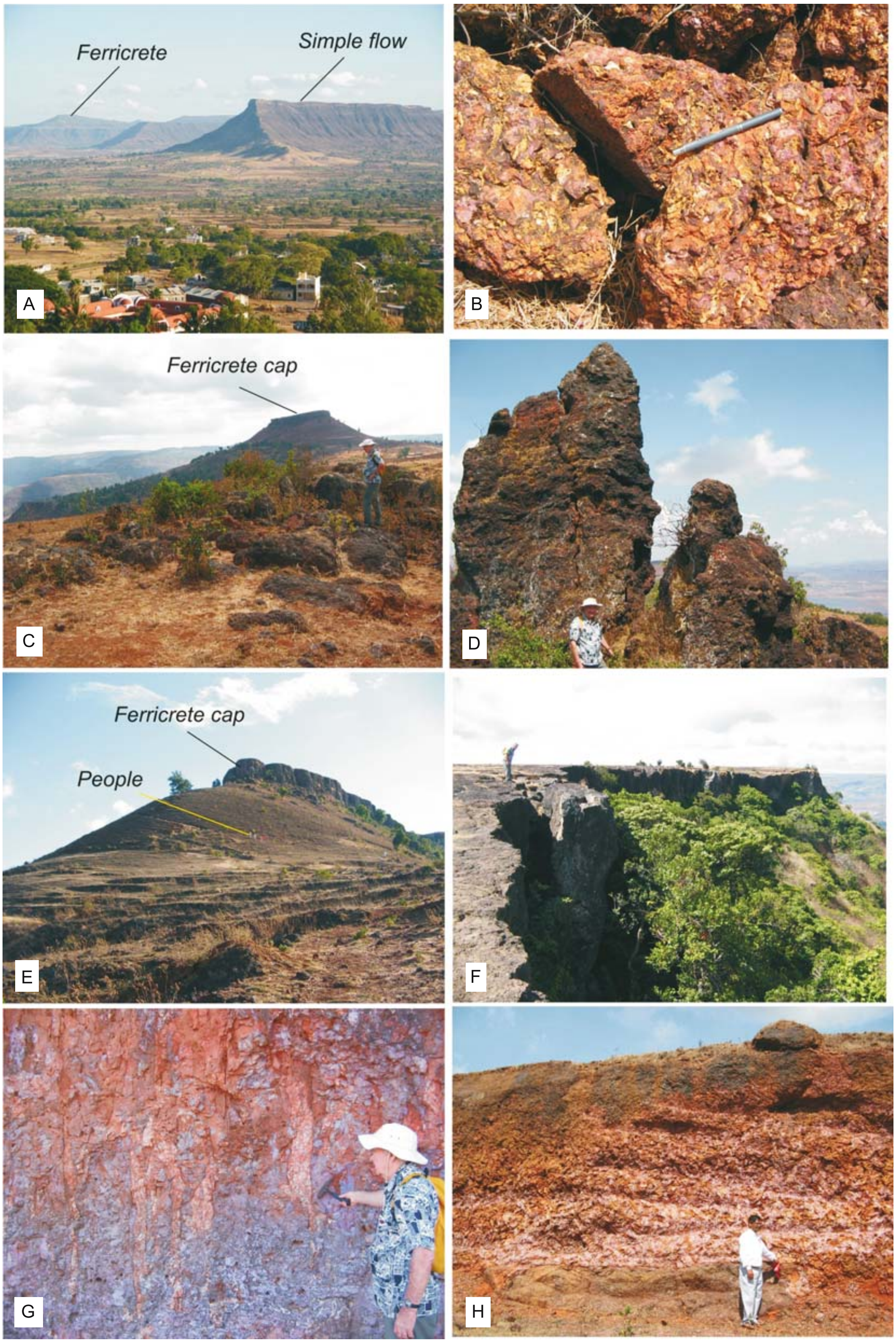

Figure 6. (A through H). Field photographs from the Satara–Patan–Koyna region. See text for explanations.

saprolite has been eroded out. The ferricrete base again has 'egg-board' undulations. This may be the pseudokarst of Kale (2000). It is impossible to descend further here. On the southern edge of the tableland large blocks of the ferricrete are 'peeling off' the plateau edge (figure 7C), as at Sadavaghapur. On the northeastern end of the tableland, a roadcut between the tableland and another

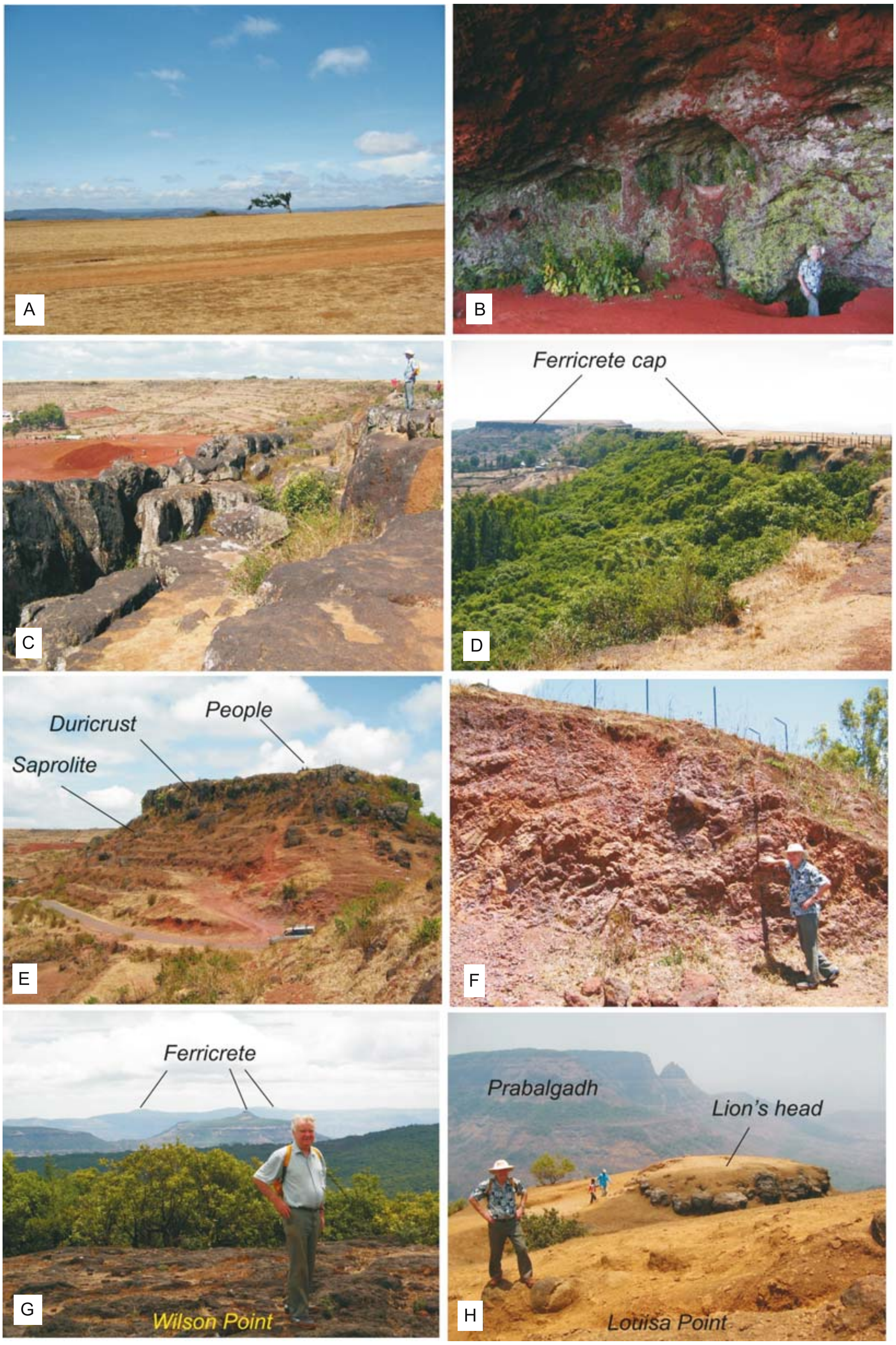

Figure 7. (A through H). Field photographs from the Panchgani–Mahabaleshwar–Matheran areas. See text for explanations.

ferricrete-capped mesa to the northeast (figure 7D) exposes a good section through the 25-m-thick ferricrete and the saprolite below (figure 7E). The saprolite shows large fractures (figure 7F) as well as joint blocks undergoing incipient spheroidal weathering. No mottled or pallid zone exists. A little to the west, a small section behind a peppermint factory shows orange-brown saprolite.

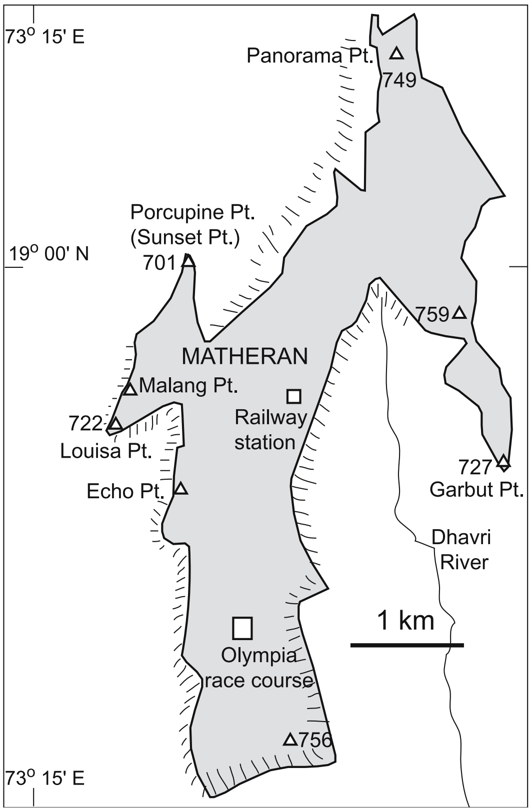

Figure 8. Map of the Matheran tableland with elevations (in metres) and locations visited.

Mahabaleshwar is a large duricrust-capped plateau with its highest elevation (1436 m) at the centre in a forest. At the lookout point named Arthur's Seat (1347 m) situated on the edge of the Western Ghats escarpment ∼20 km north of Mahabaleshwar, and with a grand view of a >1-km-thick sequence of the Deccan basalts, ferricrete overlies brown saprolite. On the eastern side of Mahabaleshwar, Wilson Point (∼1430 m) looks towards Panchgani, and again shows ferricrete underlain by saprolite with fractures and some spheroids intact. This is a duricrust boulder field (figure 7G), similar to the one at Sadavaghapur.

3.3 *Matheran*

Matheran (760 m, figure 8) is an isolated forested plateau west of the Ghats escarpment, rising prominently from the Konkan Plain. Matheran is lower than the edge of the Deccan at Bhimashankar (1005 m, figure 1b). It is debatable whether the duricrust on Mathern is most like that on the High Deccan or like that on the Konkan Plain.

We visited outcrops at the scenic viewpoints on the western edge of the plateau (∼750 m, figure 8). At Echo Point, we found ferricrete boulders forming high ground underlain by the distinctive local red soil and below the soil the saprolite (with joints and spheroids). The Malang and Louisa Points show the same sequence, of ferricrete above, saprolite below, and fresh rock underneath it. The 'Lion's head' at Louisa Point (figure 7H) is made up of fresh, jointed basalt, and ground to the east of it (the Point itself) shows the jointed, spheroidally weathered saprolite. At Porcupine (Sunset) Point, duricrust boulders overlie jointed, spheroidally weathered saprolite, which then passes into fresh basalt below. Nowhere on Matheran did we find a mottled or pallid zone. Mishra *et al* (2007) report that "the Matheran plateau has a colluvial-laterite regolith, attaining a thickness of >100 m ..." We have not found such thicknesses, and think the maximum would be 20 m. They also report that "All zones of mature laterite profile can be identified, but no *in situ* profile could be observed, as the pile of debris obscures it." We agree that no whole profile is visible, but we did not even see isolated patches of a pallid zone or concretionary zone.

3.4 *Summary of field observations*

Average thickness of the ferricrete duricrust throughout the large region we have covered is 20 m, which is unusually high. Even at the best outcrop locations, we have not observed even a single typical 'laterite profile' of the kind shown by Widdowson and Gunnell (1999, their figure 4) for the Konkan Plain. At each locality, we see that the ferricrete duricrust directly overlies the saprolite which may have patches of different colour, and have mottles, mega-mottles or colour banding. There is no pallid zone. The saprolite passes downward into fresh basalt.

4. Duricrust distribution: Dissected high plain or inversion of relief?

The present distribution of high-level duricrust (figures 4, 5; based on Widdowson 1997) could be achieved in at least two ways (figure 9), and the two would have different tectonic implications:

(1) Formation of ferricrete across a vast plain as a continuous blanket, and then erosional destruction of most of it to leave the ferricretes at mesa tops (Widdowson and Cox 1996; Widdowson 1997). This is illustrated in figure 9(a).
(2) Formation of the duricrusts along drainage lines, followed by inversion of relief (e.g., Pain and Ollier 1995). This is illustrated in figure 9(b).

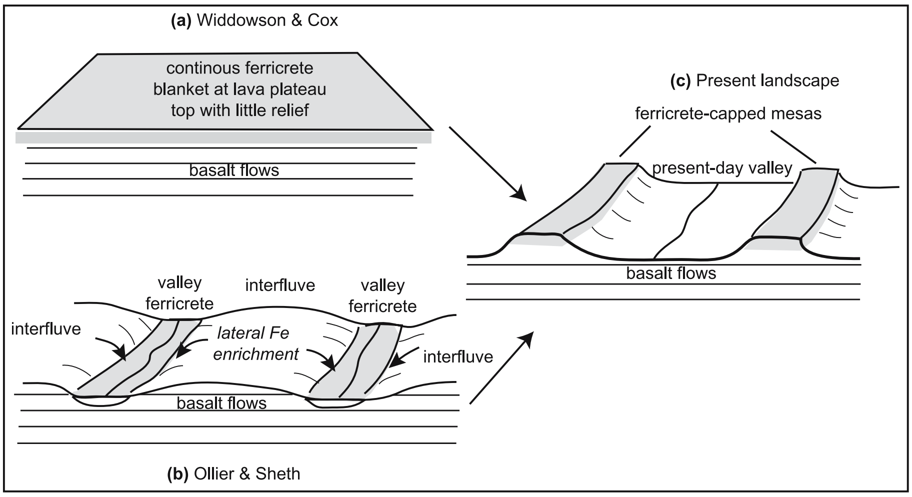

Figure 9. Illustrations with vertical exaggeration of **(a)** model of Widdowson and Cox (1996) and Widdowson (1997), showing the ferricrete (grey) as a continuous blanket on a late Cretaceous palaeosurface that is the top of the basalt lava pile. No relief inversion is implied. **(b)** Model proposed here, showing the ferricrete only forming in river valleys separated by highland areas of the basalts. Relief inversion is required. The present-day scenario is shown in **(c)**, which both models explain in very different ways.

4.1 *The ferricrete plain hypothesis*

Several early workers envisaged laterites covering entire landscapes, usually peneplains. Jutson (1914) shows production of the present landscape with laterite-capped mesas by widespread erosion down to the weathering front. Woolnough (1927) had the same idea, and conjured up the vision of an Australia-wide Miocene laterite-capped peneplain. Walther (1915) seems to have had this idea in his classic early paper, though one of his figures (figure 3) shows that he was aware of some role for valleys and unconformities. In our study area Widdowson and Cox (1996) and Widdowson (1997) argued that the roughly accordant ferricrete mesas around Mahabaleshwar and forming the summits of the Bamnoli Range (figures 4, 5) are the remnants of a once-continuous (but now largely destroyed) ferricrete blanket on the lava pile (see also Sheth 2007 for a discussion).

The main problem with this idea is from where to obtain enough iron. Most writers, thinking of the development of ferricrete profiles like giant test-tubes, derive the iron from either above or below. Derivation from below was an early favourite, with variations on the theme such as iron moving up by capillary action, or being brought up in each successive wet season. Profiles with a pallid zone at depth gave some support to the idea: the pallid zones had evidently lost iron and the duricrust had gained it, so it went from one to the other. Quantitatively the amounts of iron do not match up, but in any case, for the High Deccan duricrusts there is no pallid zone. Derivation from above is another possibility. This might be by the unlikely event of blowing in iron-rich dust (Dubois and Jeffrey 1955; Kisakurek *et al* 2004), or simply weathering upper rocks and transporting the iron down-profile to make a duricrust, and then eroding away the upper leached part of the profile. If this happened on the High Deccan then the removal of anything above the duricrust has been extremely effective.

4.2 *The inversion of relief hypothesis*

The inversion of relief hypothesis is that the ferricrete caps forming the present summits of the duricrusted mesas today were formed in a river valley system, and these original valleys have since been inverted as the surrounding, softer weathered basalts have been eroded to a greater extent. We explain how the duricrust could be formed in valleys, how inversion can come about, and present the evidence to suggest that this happened.

The idea of lateral accumulation accompanied by inversion of relief was propounded by Maignien (1959, 1966) to account for laterite duricrusts in Madagascar. Many other workers (e.g., Folster 1964; Rhodenburg 1969; Pain and Ollier 1992, 1995; Schwarz 1994; Ollier 1995) have noted that much modern ferricrete forms on footslopes or floors of river valleys. They attribute its formation to lateral movement of iron in solution rather than vertical movement. Lateral enrichment means a much larger area from which to bring the iron. Lateral movement of water on hillsides carries weathering products from upper slopes to lower sites, where drainage is often impeded and so chemical precipitation is likely. As Ollier and Pain (1996, p. 185) showed it is much easier to enrich a valley bottom, so that entire interfluves are available as

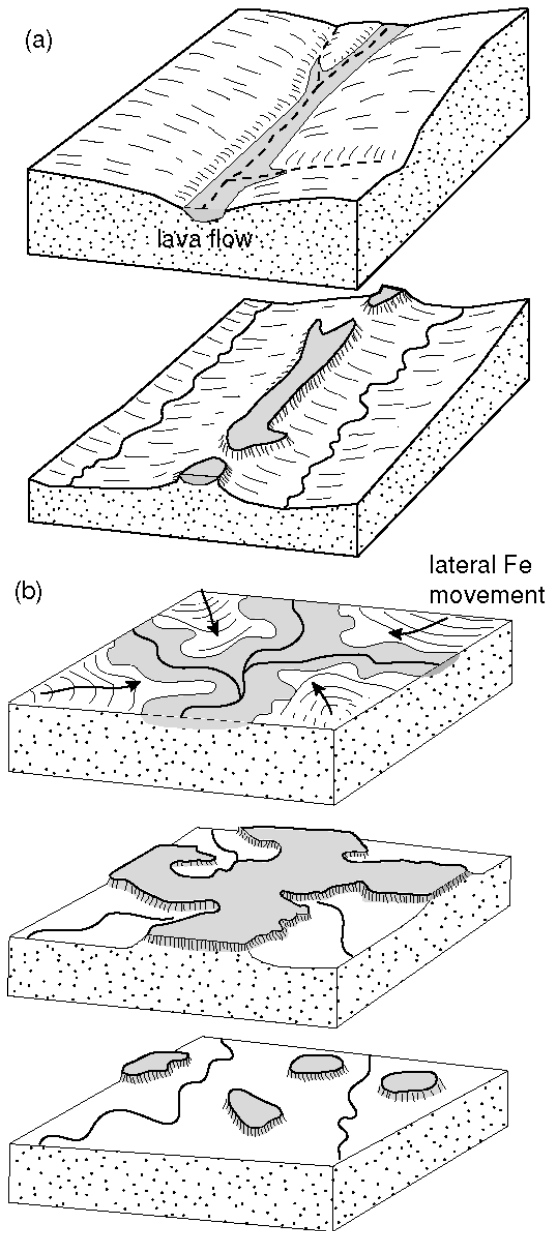

Figure 10. Inversion of relief. **(a)** A lava flow fills a valley; original streams are shown as dashed lines. New lateral streams form on each side of the lava flow, and downcutting and valley widening by them leave a lava mesa. Based on Ollier (1988). **(b)** The floor and lower slopes of a river valley system are partly covered with alluvium and colluvium which are cemented to form ferricrete. Later erosion attacks neighbouring weathered rock and the resistant ferricrete now forms mesas. Based on Pain and Ollier (1995).

iron-shedding areas and only relatively narrow valley bottoms need to be enriched (figure 9b). The idea has been extended to many different kinds of duricrusts, in many parts of the world (Pain and Ollier 1995).

But if much modern ferricrete is forming in valleys, why is older ferricrete found so frequently on plateau tops? The reason is inversion of relief (figure 9c). This is most easily understood for lava flows. A lava flow can enter a river valley, and downcutting of the sides of the resistant lava flow by new lateral streams leaves a lava mesa or ridge surrounded by lower ground (figure 10a). Induration of a valley bottom with hard ferricrete leads to a similar situation (figure 10b). Thousands of kilometres of inverted relief have been reported from Australia (figure 11 and, e.g., figure 41 of Twidale 2004) and other continents, and relief inversion is a very important but often overlooked factor in landscape evolution (Pain and Ollier 1995).

The chief line of evidence in support of the relief inversion hypothesis for the High Deccan ferricretes is their outcrop pattern. The duricrust maps of Widdowson and Cox (1996) and Widdowson (1997) (figures 4, 5) in the Mahabaleshwar–Koyna area reveal a perfect dendritic pattern in the Bamnoli Range. The pattern is in long thin outcrops, like shoe-strings. This does not look like the pattern of a dissected plateau surface, for that would have broad patches of the top layer, as seen for instance in topographical maps of the Grand Canyon. Furthermore the 'strings' appear to have a branching pattern, like the dendritic pattern of a simple river system. This can be particularly appreciated on Google Earth images of the Bamnoli Range. On this basis we suggest that these mesas represent an inverted palaeoriver valley system. The roughly even width of the mesas in the Mahabaleshwar–Koyna area provides palaeovalley widths of ~ 1 km. Isolated ferricrete-capped mesas exist far to the south of Koyna (figure 4) but are so few and isolated that no pattern can be recognized.

We thus suggest that the ferricretes never formed a continuous blanket but formed in a palaeoriver system, with interfluves of the basalts. Subsequent erosion and relief inversion have produced the present landscape. In this scenario, the duricrusts no longer mark the original top of the Deccan basalt pile, but the duricrusted floor of a palaeoriver system which we will call the Bamnoli palaeoriver.

The chief argument *against* the valley-bottom (and relief inversion) hypothesis can be that there are no valley bottom deposits associated with the High Deccan duricrust. We have seen no definite alluvium at the base of the ferricretes, though there is possibly a 5-m-thick layer of weathered pebbly alluvium at Parambe village. However, basalt does not produce the abundant quartz pebbles and thus stone-lines such as those described from valley-bottom ferricretes in Australia, for example. Deep weathering on a basalt plain is likely to produce only clay, which would be hard to recognize in a weathered profile. Present-day streams crossing the Konkan plain carry small pebbles of basalt, but again these might not survive

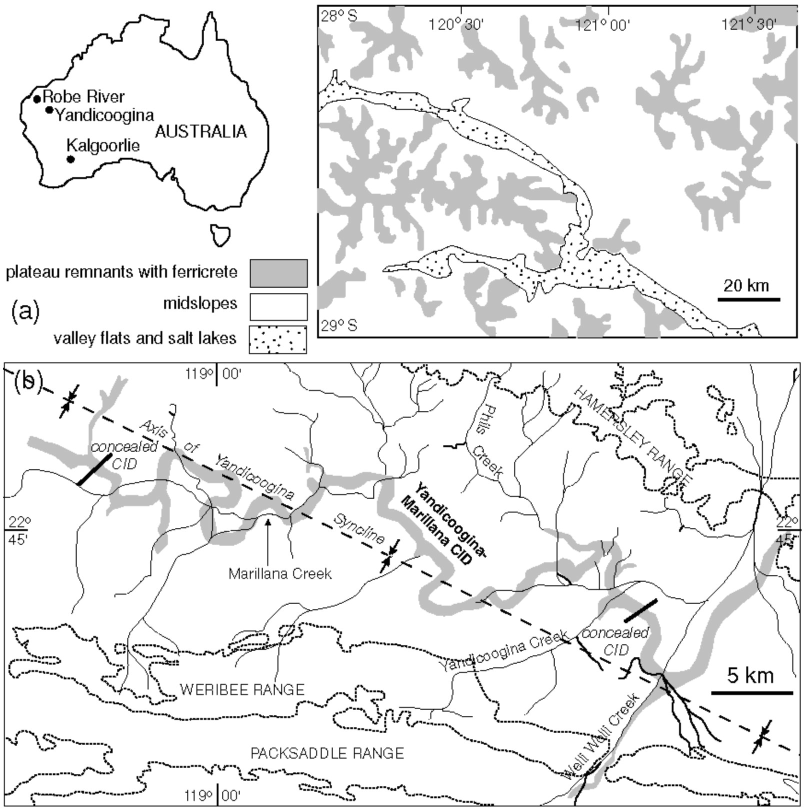

Figure 11. **(a)** Dendritic pattern of ferricrete remnants, Kalgoorlie, Western Australia (after Chan *et al* 1988; Ollier 1995). **(b)** Map of the Yandicoogina-Marillana channel iron deposit (CID), Western Australia, based on MacPhail and Stone (2004).

the great weathering that made the thick duricrust of the Bamnoli Range.

Widdowson and Cox (1996) used the Zr/Nb ratio to support their postulate that the ferricrete represents almost the original top of the lava pile, i.e., the transformed uppermost lava flows (Panhala Formation), allowing for the stripping of 150–200 m of lavas from above the duricrusts as also inferred by Walker (1969) based on zeolite zones. The inversion of relief hypothesis that we propose here is also consistent with this view, as we do not argue for substantial relief in the landscape. The relatively close spacing of the ferricrete-covered tributaries suggests that the interfluves could not have stood much higher than the valleys (100–200 metres), and the fact that the modern ferricrete-capped mesas are flat shows that the palaeovalleys were more or less flat. However, the ferricrete mesas do not mark the original top of the lava pile but a phase of fluvial erosion within it. This is not a minor point, rather, this case study can be immediately perceived as identical with many identical case studies worldwide involving ferricretes and relief inversion. Widdowson and Cox (1996) and Widdowson (1997) suggested that no significant erosion of the lavas occurred before the development of the ferricrete cap. If there has been inversion of relief, a significant time gap must have occurred between the eruption of the last lavas, the formation of valley ferricretes, and the inversion of relief.

It is of interest and considerable relevance here that relief inversion has already been invoked for the Tertiary ferricrete mesas of the Konkan plain (figures 1, 4), as well as the clearly detrital laterites with sedimentary structures at Khanapur on the Deccan Plateau (Elzien 1992; Kale 2000). According to Gunnell and Radhakrishna (2001, p. 114), many of the Konkan ferricretes formed in river valleys, and relief inversion has left them today as resistant interfluves between west-draining streams. For the laterite profile at Bidar, Kisakürek *et al* (2004) argue on the basis of lithium isotopes for purely vertical chemical relationships, supposing that there were no basalt lavas at a higher level than the preserved ferricretes. But Bidar forms a major interfluve between the Bhima and Godavari Rivers (figure 1), which is perhaps not accidental in the light of the inversion of relief hypothesis. Interestingly, based on the concentrations and isotopic ratios of rhenium and osmium in the Bidar ferricretes, Wimpenny *et al* (2007) consider lateral input by solute-laden groundwaters as necessary. If such groundwaters brought in these

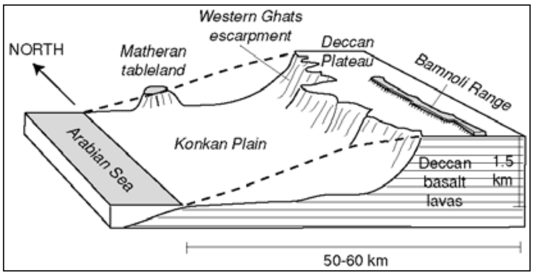

Figure 12. Diagrammatic representation of the main features of the area of study (vertical exaggeration ∼40X). The Great Escarpment separates the Deccan Plateau from the Konkan Plain. The duricrusts on the Deccan Plateau cap smaller plateaus, including the Bamnoli Range which is a very long, linear feature. Ferricrete duricrusts are shaded. The Matheran Plateau may be a downwarped remnant of the Deccan Plateau (as shown), though some consider it a remnant of a lower erosion surface.

elements, they could have brought in many others, iron included.

5. Tectonic implications and the original ferricrete distribution

Widdowson and Cox (1996) and Widdowson (1997) contoured the base of the ferricrete south of Mahabaleshwar, and interpreted the resultant map as showing a south-plunging anticlinal structure (figure 5), which they related to post-eruptive deformation of the whole sequence. This interpretation is based on the assumption that the ferricrete, and presumably the plain it formed on, was horizontal to start with.

If the inversion of relief scenario and river-valley formation of the ferricretes are valid, quite different tectonic interpretations result. In normal, dendritic drainage the V's formed by the intersection of tributaries and a main river always point downstream, so the Bamnoli palaeoriver must have flowed in a N–NW direction. The modern drainage flows S–SE (figure 5), so drainage reversal has evidently occurred. In this case, the elevations on the base of the basalt simply indicate relative uplift to the north, which would be the cause of the reversal of drainage direction, now away from Mahabaleshwar. This is to say that the originally N–NW-sloping Bamnoli palaeoriver system has been back-tilted with a minimum differential uplift of 280 m.

The great thickness of the High Deccan duricrusts, and the fact that they are totally absent from the weathering gaps within the Deccan Traps and never reproduced in younger duricrusts suggests that there was a unique, long period of duricrust formation. We think this was most probably disrupted by the known tectonism that had several effects. The coastal slope was increased by downwarp to the coast (Ollier and Pain 1997). Valleys incised deeply, and the new geomorphic situation never again allowed the development of ferricretes as thick as those of the High Deccan. On the Deccan Plateau itself tectonic movement reversed the flow directions of some rivers. Mishra *et al* (2007) suggest that the Matheran duricrust represents an independent lateritized surface distinct from both the High Deccan and the Konkan duricrusts, and also encounter this surface at 630 m elevation in the Indrayani river valley east of Lonavala (figure 1b). However, the gentle coastward downwarping model proposed by Ollier and Pain (1997) explains how the same High Deccan duricrust (at 1300–1400 m in the Ghats) can outcrop to the west at lower altitudes, such as the 750 m elevation on the Matheran Plateau, located 20 km west of the escarpment (figures 1b and 12). Notably, this downwarping model implies a westward tilt of only ∼1–2°, and this downwarping is not to be confused with the Panvel flexure (Sheth 1998).

Ferricretes are absent from the Ghats and Deccan Plateau region north of Pune, and it has been speculated (Raja Rao 1984) that ferricretes may have preferentially developed over aa flows of the southern Deccan, not the compound pahoehoe lavas that dominate the northerly areas. It is noteworthy however that workers such as Raja Rao (1984) have wrongly described the 'simple' flows (long sheets typically with columnar jointing) that dominate the southern Deccan as aa (Bondre *et al* 2004; Sheth 2006; Duraiswami *et al*, in press). Also, the well-developed duricrusts on Matheran, which is a wholly compound pahoehoe lava sequence (Neral and Thakurvadi Formations), show that ferricrete duricrusts develop on any kind of basalt. Notably, in the topographic maps for the Satara region and Bamnoli Range, even the contours of the lower plateaus, from which the ferricrete has been stripped, show a distinct dendritic pattern. We believe that the valley-formed ferricrete is the cause of this, and similar lava plateaus with dendritic map patterns (see figure 4 of Kale and Shejwalkar 2007) in the ferricrete-free areas north of Pune (figure 1) were once overlain by ferricrete, now stripped.

6. Discussion of laterite and laterite formation: Relevance of present observations

A number of general ideas or paradigms relate to the formation of ferricrete, 'laterite', or duricrusts in general, and our observations highlight some of these.

6.1 *Zones of a laterite profile*

In section 2, we outlined ideas about the typical laterite profile. This now appears to be something of a myth, and a wide range of materials have been described as 'laterite'. In the High Deccan ferricretes the concretionary and pallid zones are absent, and the only 'zone' left is what might be described as 'indurated mottled zone.' Unfortunately the concept of the classical profile seems to dominate thinking, and there has been a tendency to look for the classical zones, and apparently find them.

6.2 *The indurated saprolite idea*

Ollier and Rajaguru (1989) re-described the laterite from the classical area at Angadippuram where Buchanan (1807) first described laterite. They found two interesting features:

(1) Buchanan described the laterite as soft when first dug up and then hardening by drying. Over the years textbooks repeated the story until in some account the freshly dug laterite was described to be as soft as butter. This is not true, and the laterite is only cut with axe-like tools. It is hard enough to be used straight away, and is merely stored until required, not to dry out.

(2) There is an upper, very vesicular crust, but this is only utilised for rough work like dry-stone walls. The commercial 'laterite' is what would be called, in the classical profile, the mottled zone and it is pure saprolite. In southern India rare quartz veins are seen in the laterite quarries, but the quarrymen avoid such material with veins as the laterite blocks break up along them and cannot be sold. It is vesicular, with mainly vermiform tubes, and no pisolitic structures. Of course on the Deccan basalt there are no quartz veins, but occasionally joint structure extends into the lower part of the duricrust, and we have no doubt that the High Deccan duricrust is indurated saprolite.

In short, Ollier and Rajaguru (1989) reported that the classic 'laterite' is somewhat indurated saprolite, and as it is mottled they thought it was equivalent to the 'mottled zone' of the classical laterite profile. On the Matheran Plateau, we observed laterite blocks being used for paving roads. At first sight they looked like the local duricrust, but on enquiry we were told that they were brought up from the Konkan coast (Ratnagiri, figure 1), as the local ferricrete cannot be quarried by law because of environmental concerns. The Matheran duricrust is in fact too hard to use at present, and the softer (though still hard enough) Konkan laterite is similar to that at Angadippuram.

6.3 *The unconformity idea*

Ollier and Galloway (1990) pointed out that many laterites in many parts of the world were not simple weathering profiles formed on the underlying bedrock (though much geochemical analytical work has been based on this assumption). There was usually an unconformity between some overlying material, such as alluvium or colluvium, and weathered bedrock beneath. The hydrological contrast at the unconformity made it a favourable place for precipitation of iron. In some instances there were contrasting types of ferricrete, such as pisolitic ferricrete above the unconformity and vesicular ferricrete in the saprolite beneath, as described from Uganda (Ollier 1959).

In the duricrusts of the High Deccan there is no trace of any such unconformity. In many ferricretes in Africa and Australia a stone-line often separates the two parts of the profile, but there are no stone-lines in the High Deccan duricrust because there are no quartz veins to provide the stones.

6.4 *Laterite and ferricrete definitions*

Widdowson (2004) defines *ferricretes* as "those duricrusts which incorporate materials non-indigenous to the immediate locality in which the duricrust formed" and states that the term should also be extended to "those materials whose constituents have been substantially augmented by the precipitation or capture of elements and compounds from allochthonous fluids". He defines *laterites* as "iron-rich duricrusts which have formed directly from the breakdown of materials in their immediate vicinity, and so do not contain any readily identifiable allochthonous component". If so what do we call the High Deccan duricrusts which probably developed in river valleys on weathered basalt enriched in iron derived laterally dissolved in groundwaters? Whereas Widdowson (2004) is correct in noting that many ferricretes contain allochthonous (external) components, we think that the term 'ferricrete', preferable over 'laterite', is best applied to the *iron-cemented*, hard materials (duricrusts) found on plateau remnants, whatever their mode of origin (e.g., Ollier and Pain 1996), and 'laterite profile' can be used for a complete profile which however may also well incorporate externally derived materials.

6.5 *'Autochthonous' and 'allochthonous' ferricretes: A blurred distinction*

The High Deccan ferricretes cannot be considered vertical test tubes. If the inversion of relief hypothesis is correct, they necessarily incorporated laterally derived materials (see also Wimpenny *et al* 2007). At the same time they do not involve any really external (non-basaltic) components, because the modest highlands we envisage as having formed the interfluves were of basalts. Additionally, because the High Deccan duricrusts developed on the floors of palaeovalleys, they do not overlie the basalts below with an unconformity. These ferricretes therefore cannot be grouped cleanly into either the 'autochthonous' or the 'allochthonous' categories. We wonder if there are *any* ferricretes that are truly and purely one of these (cf. Widdowson and Gunnell 1999).

7. Conclusions

The High Deccan ferricrete duricrusts are distinctive, very thick (20–25 m), and unlike many others. They consist of indurated saprolite overlying thick, non-indurated saprolite. The duricrusts are almost entirely massive with vermiform vesicles, with no pisolitic or concretionary zone, and no pallid zone beneath. They do not have any associated alluvium, and do not rest on unconformities. The High duricrusts have been interpreted as weathering products on the original top surface of the Deccan Traps, but there is evidence that they may be valley-bottom formations preserved after inversion of relief. In fact, it is only this hypothesis that explains their unusual combination of characteristics. The hypothesis also leads to definite and important conclusions about post-Deccan tectonics and the original extent of the ferricretes. However, the general problem of defining 'laterite' becomes even more difficult, and we may have reached the stage when the very concepts of 'laterite' and 'lateritization' are hindering progress in regolith research.

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