MICROMORPHOLOGICAL ANALYSIS AND CHARACTERIZATION OF 70 BENCHMARK SOILS OF INDIA

A basic reference set

Part I

...OIL SURVEY INSTITUTE, WAGENINGEN - 1982

MICROMORPHOLOGICAL ANALYSES AND CHARACTERIZATION OF 70 BENCHMARK SOILS OF INDIA

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Part I: General

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NETHERLANDS SOIL SURVEY INSTITUTE, WAGENINGEN - 1982

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P R E F A C E

This reference set contains the full documentation of the micromorphology of 70 Benchmark soils of India, carried out as an integral part of a bilateral project between India and The Netherlands, titled: Establishment of a soil micromorphological unit and micromorphological analyses and characterization of Benchmark soils of India. The main objective of this project is to establish an independent, well-functioning soil micromorphology unit for the Indian National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur. The micromorphological study of the Benchmark soils is performed at the Netherlands Soil Survey Institute in co-operation with the International Soil Museum. Mr. D. Schreiber of the International Soil Museum accurately produced the large number of thin sections in a relatively short time. The micromorphological study, consisting of descriptions, interpretations and the integration of the results, is performed by Dr. M.J. Kooistra of the Netherlands Soil Survey Institute.

Thanks for their generous co-operation and co-ordination in the realization of this report are particularly due to:

- The National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur, India and collaborating Agencies.
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THE DIRECTOR OF THE
NETHERLANDS SOIL SURVEY INSTITUTE

Ir. R.P.H.P. van der Schans.

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SUMMARY

This reference set contains the full documentation of the micromorphology of 70 Benchmark soils of India, and forms an integral part of a bilateral project between India and The Netherlands. One of the main objectives of this project is to provide the Indian National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur with a basic reference set containing the micromorphological analyses and characterization of selected Benchmark soils.

The soil series that qualify for consideration as Benchmark soils are selected by soil scientists from the Central and State Departments of Agriculture, Forestry and Irrigation, the ICAR institutes, and Agricultural Universities in India, on the basis of available information. Benchmark soils are those soils that occupy a key interpretative position in the soil classification framework and/or cover a large area (Murthy, R.S. et. al. (Eds), 1982). Teams of 5 - 6 soil scientists selected, examined and sampled the pedons from Benchmark soils at appropriate sites. The samples for micromorphological research were sent to The Netherlands to be studied at the Netherlands Soil Survey Institute in co-operation with the International Soil Museum, Wageningen. The full micromorphological documentation consists of: a standard description of each thin section; if more than 2 thin sections of a pedon were available, a short micromorphological description augmented by a few black-and-white photographs of the main features; and the interpretation of the data.

In a number of cases a conclusion or a remark has been added in which changes in profile description and soil classification are proposed. The full micromorphological documentation is presented together with essential basic information, needed for interpretation of the data, provided by the National Bureau of Soil Survey and Land Use Planning. In general, the latter information consisted of: information about the site, a detailed profile description, land use information and analytical data. This presentation enables the reader to relate the micromorphological study to aspects of soil science and agriculture, and allows the documentation set to be used as an independent reference set.

Some of the micromorphological information has been used previously for special micromorphological texts in "Benchmark Soils of India" (Murthy, R.S., et. al. (Eds), 1982), in tour guides for the 12th International Congress of Soil Science, New Delhi, 1982 and in an exhibition of mono-

liths held during that congress. The chapter written for the above mentioned Benchmark publication, giving a short overview of the micromorphology of the Benchmark soils studied , has been included in this report. The micromorphological study resulted in an increased understanding of past and present processes operating in soil. This information has been used to propose changes in profile descriptions, to revise field classifications, and has added new dimensions to the results of physical and chemical analyses. Lastly, the major impact of soil management practices which had hitherto been virtually ignored in the field was recognized. From these results it can be stated that this micromorphological study has made a functional, specific contribution to our knowledge and understanding of these Benchmark soils. Some recommendations for future micromorphological research are presented.

INTRODUCTION

Soil micromorphology is an essential requirement for soil characterization and classification, important for the proper placing of soils according to international classification systems and for assessing linkages between soil and production for micromorphological research. Facilities and knowledge about micromorphology are not yet available in the National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur, India, which was entrusted with the responsibility of compiling a study of Benchmark soils of India based on soil surveys carried out by various Indian agencies, in co-operation with other national and state agencies and the agricultural universities engaged in soil survey work. To coincide with the 12th Congress of the International Society of Soil Science, held in 1982 in New Delhi, the first publication on Benchmark soils, "Benchmark Soils of India" (R.S. Murthy et al., Eds.), was issued.

The strong need for micromorphological facilities and knowledge within the National Bureau of Soil Survey and Land Use Planning resulted in a bilateral project being set up between the governments of India and The Netherlands. The main objectives of this project are: to establish a permanent indenpendent soil micromorphology unit for the National Bureau of Soil Survey and Land Use Planning and to provide it with a basic reference set containing the full micromorphological documentation of the first selection of Benchmark soils. This reference set is the basic reference mentioned as one of the main objectives of the project.

MATERIAL

Benchmark soils are soils that occupy a key interpretative position in the soil classification framework and/or cover a large area (Murthy, R.S. et al. (Eds), 1982). Soil series that qualify for consideration as Benchmark Soils are selected by soil scientists of the Central and State Departments of Agriculture, Forestry and Irrigation, the I.C.A.R. Institutes and the Agricultural Universities, on the basis of available information.
For this purpose, India was divided into 4 regions, each of which was assigned a team of 5-6 soil scientists to select, examine and sample pedons from Benchmark soils from appropriate sites. The members of the teams compiled detailed profile descriptions, assembled information about the sites, and took samples for laboratory analysis and micromorphological characterization.
The samples for micromorphological research were sent to The Netherlands. The micromorphological study of Benchmark soils started at the end of 1979 and was done at the Netherlands Soil Survey Institute in co-operation with the International Soil Museum, Wageningen, The Netherlands. Over 200 samples were sent for micromorphological investigation. During the selection, examination and sampling of the Benchmark soils, new information came to light and a number of already examined pedons were deleted and new ones added. This reference set presents the micromorphological characterization of 70 Benchmark soils. The pedons incorporated are those for which enough information was available for the micromorphological data to be interpreted reliably. The essential basic information consists of site information, a detailed profile description, land use information and analytical data on the soil sampled. All the available information about the pedons to which the samples belonged was sent to The Netherlands. This information was tentative and subject to changes, additions and modifications, and during the investigation it was updated. Subsequently it was again updated on the basis of the the results of the micromorphological study. The present report, however, contains the version of the soil information that was available at the time of the micromorphological study of the soil and that was used for the interpretation of the samples. In some cases more information was needed before the micromorphological data could be interpreted. In spring 1981, after a preliminary study of approximately 30 pedons, a Dutch micromorphologist visited India to study a selected number of the Benchmark soils in the field and to collect information on several specific topics, e.g. recent and former agricultural practices, environmental factors such as flooding, and analytical and soil genesis data.

METHODS

The micromorphology used for the study of the Benchmark soils was basically the study of thin sections with a light microscope, at magnifications of up to x 200. The thin sections consisted of 15 µm thick slices of hardened blocks of undisturbed soil material (8 x 15 cm) fixed on glass slides.
There were 4 stages in the study of these thin sections by light microscopy: 1. identification of the materials, 2. description of these materials, including their distribution and quantity, 3. interpretation of these data and 4. integration of the results in soil science and other discliplines.
Each thin section studied was described by means of a brief macroscopical characterization and a list of micromorphological characteristics grouped under three headings: structure, groundmass and special features. If more than two thin sections of a pedon were available, a short micromorphological description was composed, containing the same items: structure, groundmass and special features, and changes with depth were highlighted. The descriptions were augumented with photographs. Usually two black-and-white photographs were taken per pedon to show the most important features. Colour transparencies were also made of the same features, for documentation and teaching purposes.
The micromorphological data were interpreted for each pedon. The interpretation was based on: the micromorphological study of the thin sections presented in the descriptions; additional information gained from profile descriptions, site information, land use data, analytical data; the field study of a selected number of pedons; and information from the literature. The interpretations deal with the following aspects: 1. origin of the soil material, 2. exogenic processes, 3. soil-forming processes and 4. influence of management practices. They are presented according to the major processes identified, their occurrence, importance, and whether they are current or former processes. When the interpretation does not agree with the information provided on soil and site, conclusions or remarks are given, with suggestions for changes, additions or modifications.

PRESENTATION OF THE MICROMORPHOLOGICAL INFORMATION

The full micromorphological documentation of the selected Benchmark soils given in this report consists of: a standard descriotion of each thin section, a short micromorphological description when more than 2 thin sections are available for a pedon , a few black-and-white photographs of the main features, and the interpretation of the data. In some cases a conclusion or a remark is added in which changes in profile descriptions and soil classifications are proposed. The full micromorphological documentation of the selected Benchmark pedons is accompanied by the essential basic information provided by the National Bureau of Soil Survey and Land Use Planning, which usually consists of site information, a detailed profile description, land use information and analytical data. As mentioned under the heading material, the version of the soil information that was available at the time that the soil was being investigated micromorphologically is given, because the interpretation was based on this version. This comprehensive presentation will enable the reader to relate the micromorphological results to soil science and agriculture. In this way, the documentation set can be used as an independent reference set to intergrate different disciplines.

Some of the micromorphological information has previously been used for special micromorphological texts in the publication: "Benchmark Soils of India", (Murthy R.S. et al (Eds), 1982) and in tour guides for the 12th International Congress of Soil Science, New Delhi, 1982. The texts for "Benchmark Soils of India" consist of 2 parts: outlines of interpretations of the Benchmark soils and a chapter giving a short overview of the micromorphology of the Benchmark soils. Because of its importance for understanding the micromorphology of the individual Benchmark pedons, this chapter has been included in the present report. The texts for the tour guides of the 12th International Congress of Soil Science consisted of a short micromorphological description, a few black-and-white photographs, an interpretation, and a glossary of the micromorphological terms used. During the 12th International Congress of Soil Science, an exhibition of 33 of the Benchmark soils was held, for which micromorphological material and large colour photographs were prepared. This monolith exhibition forms the beginnings of a national reference collection of soils and related soil data, which will be based at the headquarters of the National Bureau in Nagpur.

The present micromorphological documentation set of Benchmark soils complements "Benchmark Soils of India" (op.cit.), as most soils are dealt with in both publications. The micromorphological documentation set includes more Benchmark soils, however, and not all the soils presented in "Benchmark Soils of India" were studied micromorphologically. Because of the complementarity between this reference set and "Benchmark Soils of India", in this set the pedons have been presented in the same order as in "Benchmark soils of India".

RESULTS AND CONCLUSION

The micromorphological study of the soils resulted in an increased understanding of past and present processes operating in soils. It enabled the origin of a number of features visible in the field and mentioned in profile descriptions to be identified. Also, many features not discerned in the field were determined and the processes responsible for them were traced. This information often resulted in proposals for changes, additions or modifications in profile descriptions and revision of the field classifications. The micromorphological information also added new dimensions to the results from physical and chemical analyses. Lastly, it enabled many features resulting from cultivation and management practices on soils to be determined. These features were often present on a large scale, sometimes dominating those resulting from soil-forming processes (chapter 4, "Benchmark soils of India") and were rarely recognized in the field.

Thus the micromorphological analysis has made a specific, functional, contribution to our knowledge and understanding about Benchmark soils.

RECOMMENDATIONS

1. In view of the specific contribution micromorphology has provided in the study of Benchmark soils it is recommended that the micromorphology unit of the National Bureau of Soil Survey and Land Use Planning be integrated in the pedology section. Micromorphological data cannot be interpreted when insufficient information is available about the site, profile, analytical data and land use. Moreover, the best results are obtained when the samples are chosen carefully in consultation with micromorphologists.
2. This study of Benchmark soils can be considered as an inventory. The results of the micromorphological analysis are valid for the pedons studied, and should only be extrapolated if the variation of the features in the same soil series is known. More pedons from the same soil series should be studied.
3. When investigating a Benchmark soil in which the field information suggests that the cambic horizon or an argillic horizon may be present, mircromorphological research is recommended.
4. Given the major impact of soil management practices, much of which results from recent short-term processes, it is recommended to study micromorphologically the effects of different types of soil management and of crop rotations in irrigated and unirrigated soil.

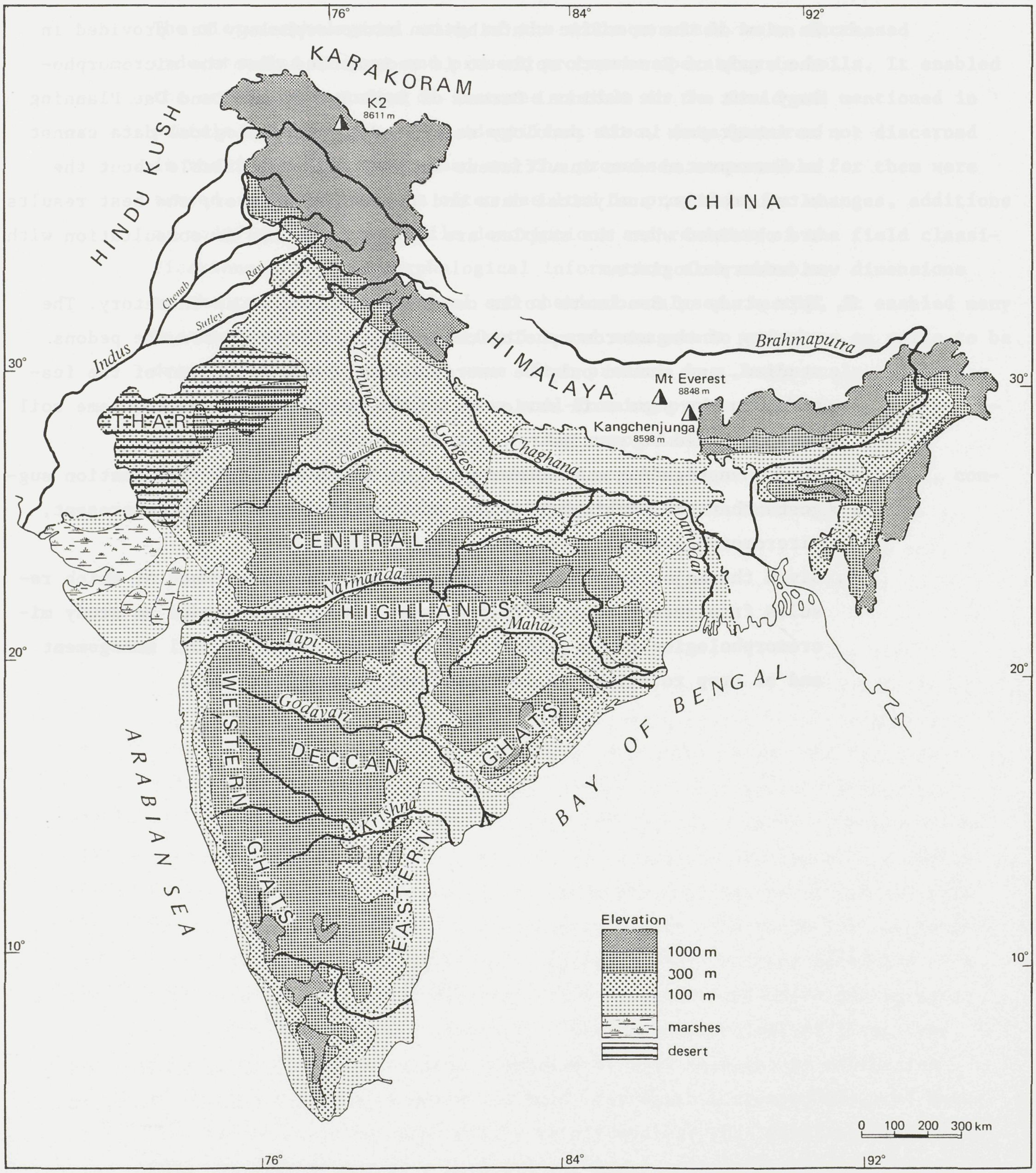


Figure 1. Physical Geography

PRESENTATION OF THE REFERENCE SET

GENERAL INFORMATION

India lies in the northern hemisphere, is 95 times larger than The Netherlands and has a total area of approximately 329 million ha. Its population is approximately 650 million, representing ca. 15% of the world population.

The Indian subcontinent can be subdivided into several main geomorphological components, viz. the Himalayas in the north; the Great Plains of the Ganges, Indus and Brahmaputra; the Central Highlands; Plateaus of the Peninsula (Deccan and Ghats) and the Coastal Areas in the east and west (Fig. 1).

The climate in different regions varies greatly because of the vastness of the country and the existence of pronounced topographical features. Large parts of the country have a semi-arid or sub-humid climate. The annual rainfall varies from 125 mm in the Thar desert in Rajasthan to 10 870 mm at Cherrapunji in Assam and the temperature at a given moment may be less than 4.5°C at Dras in Kashmir and over 45°C at Ganganagar in Rajasthan (Murthy, R.S. et al (Eds), 1982). Information about the climate is presented on some maps provided by the National Bureau of Soil Survey and Land Use Planning (Figs. 2, 3, 4).

Generally, India has a tropical monsoon climate in which most of the rain falls between June and September from the southwest monsoon. The winter or northeast monsoon is virtually dry. The monsoon climate has a strong impact on the agricultural seasons. The main agricultural season is between June and October and is known as Kharif. The winter or Rabi season is from October to April. The main crops in Kharif are jowar, rice, bajra, sugar cane, groundnut, jute, tobacco and cotton. In Rabi wheat, barley, gram, linseed, mustard, oils, peas and potatoes are grown.

Detailed information on physiography, climate, natural vegetation and land use is presented in "Benchmark Soils of India" (Murthy, R.S., et al (Eds), 1982).

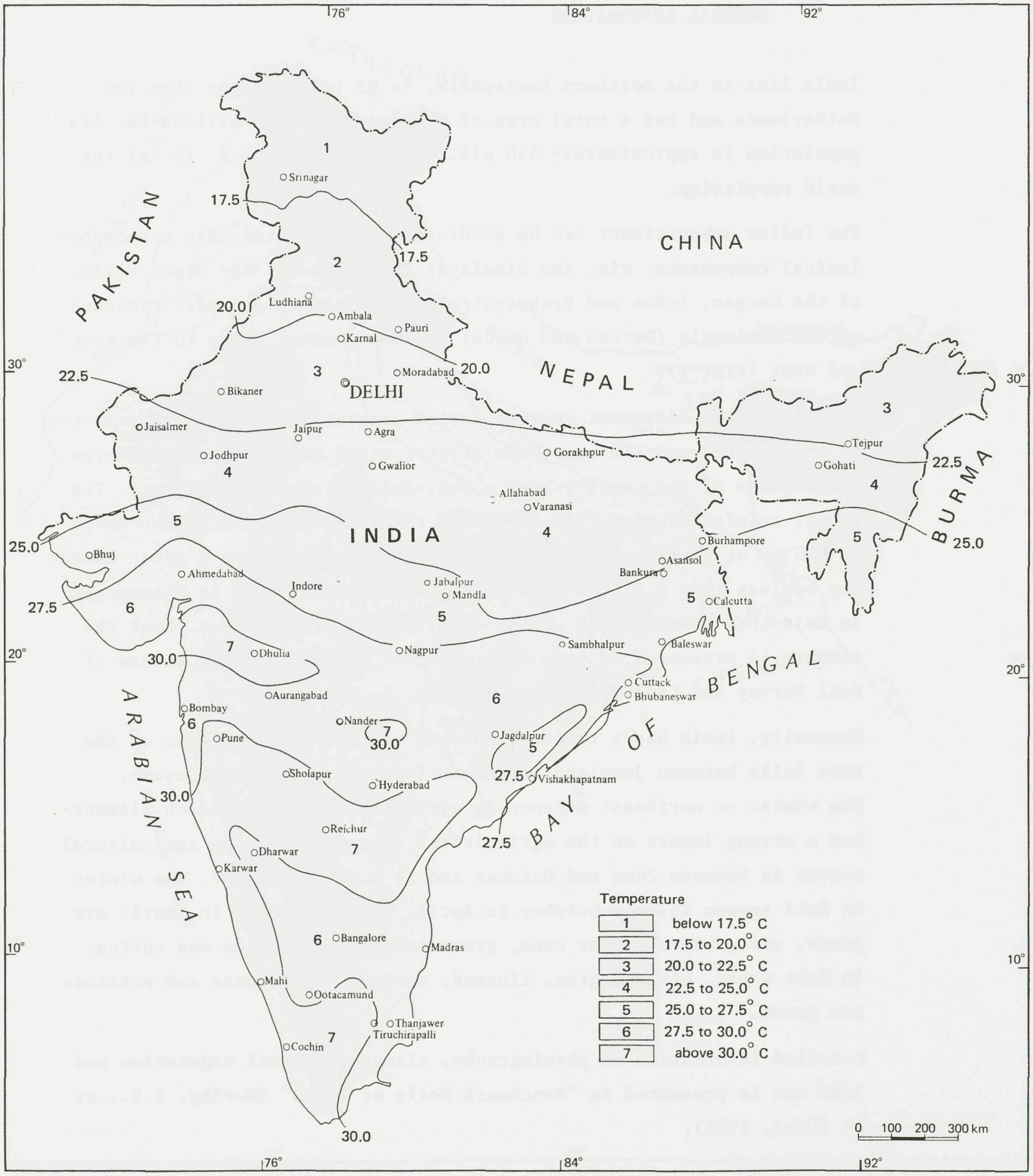


Figure 2. Mean daily maximum temperature in january (centigrade)

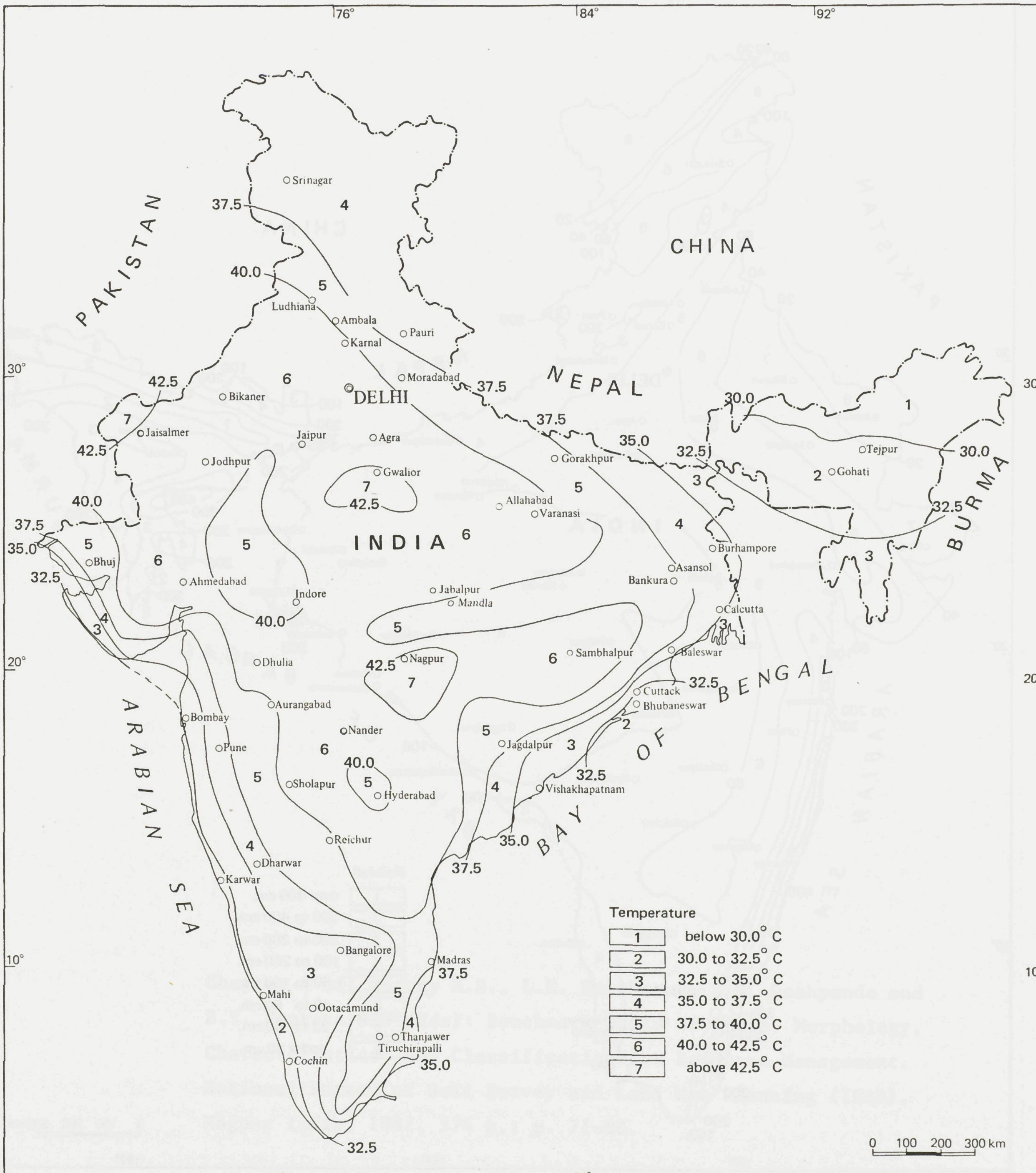


Figure 3. Mean daily maximum temperature in may (centigrade)

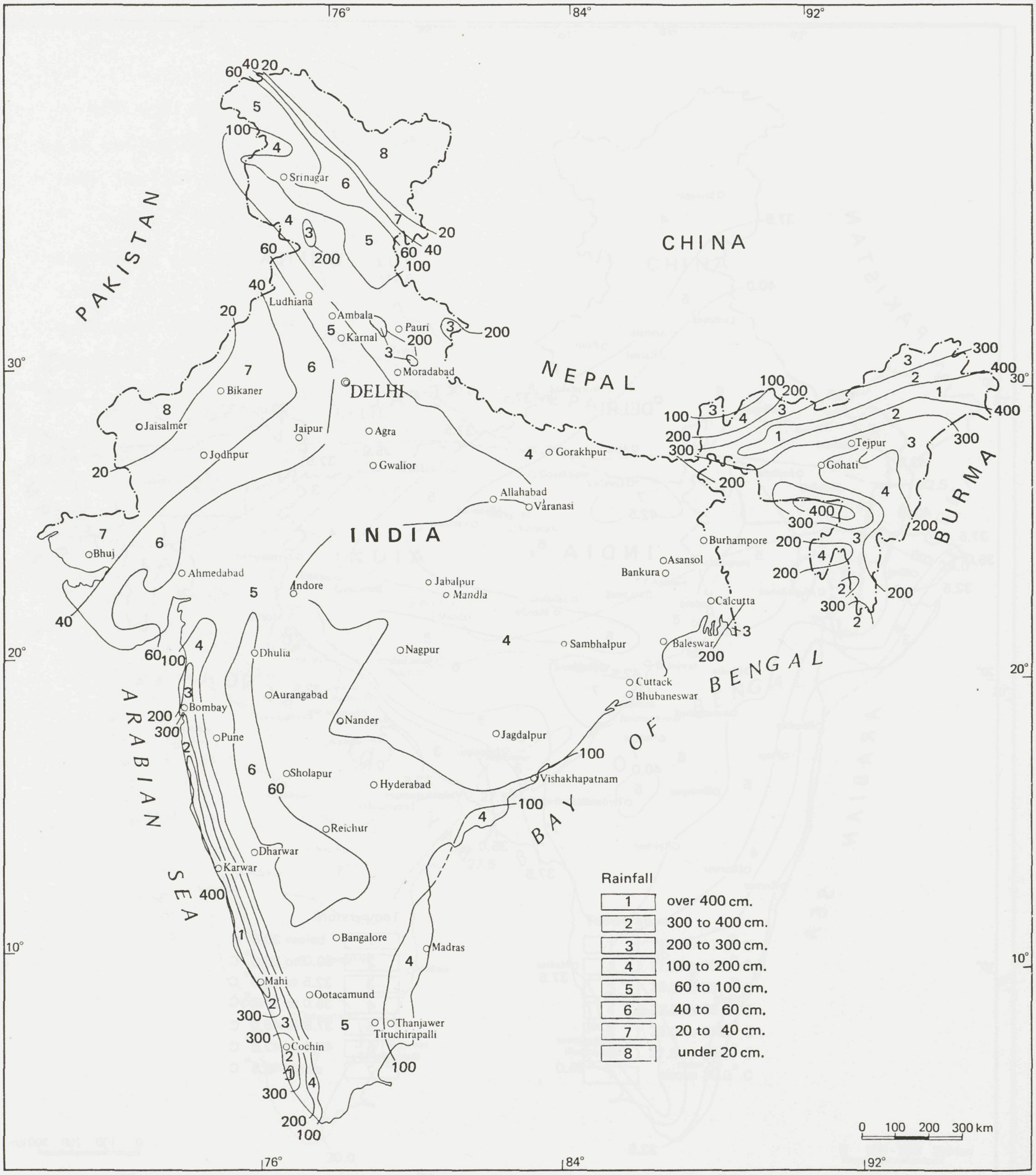


Figure 4. Average annual rainfall

Chapter 4 of: Murthy R.S., L.R. Hirekerur, S.B. Deshpande and B.V. Venteka Rao (Eds): Benchmark Soils of India. Morphology, Characteristics and Classification for Resource Management. National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur India, 1982, 374 p.: p. 71-88.

CHAPTER 4

MICROMORPHOLOGY

M.J. Kooistra

General Background .. ..

Thin Section Preparation Techniques and Study Methods ..

Terminology .. ..

Interpretation .. ..

Main Processess in Benchmark Soils .. .. ..

- Origin of the Parent Material .. .. ..
- Exogenic Processes .. .. ..
- Soil Forming Processes .. .. ..
- Influence of Management Practices .. ..

Impact of the Micromorphology on the Benchmark Soils ..

Conclusions .. ..

References .. ..

Glossary of Micromorphological Terms .. .. ..

This chapter is based on the micromorphological study of Benchmark soils. The main results of the micromorphological study are discussed and the function that micromorphology can fulfil in pedology and land use is indicated. This chapter includes (i) General background, (ii) Methods, (iii) Main Processes occuring in Benchmark Soils, (iv) The impact of Micromorphology on the knowledge of these soils, and (v) Conclusions.

GENERAL BACKGROUND

The micromorphology used for the study of Benchmark soils is basically the study of thin sections with the use of a light microscope, with magnifications up to x 200. The thin sections consist of 15 μm thick slices of hardened undisturbed soil material fixed on glass slides.

Considerable information can be gained from the study of thin sections by adopting various steps. First, the different components can usually be identified with a light microscope, but in a number of cases Sub microscopic techniques * are also necessary (Bisdom, 1981 Edn). After identification of individual soil components the location, position and relation of these constituents is examined. This information is grouped under three headings, vix., groundmass, voids and special features. Under the heading groundmass, information concerning composition, size, packing and related distribution of the soil constituents is given. The second heading deals with voids. These are spaces not occupied by solid organic or inorganic materials, and are characterised by shape, size, regularity, interconnection and intersection. Groundmass and voids form the basic pattern of the soil and many changes may occur in this pattern. These are grouped under the third heading : special features divided into two parts : (a) features related to voids and (b) features present in the groundmass. Features related to voids are found in the voids themselves, along voidwalls, and in the groundmass adjoining the voids or close to them. These features may be composed of different materials or have a packing, orientation of particles and the like which differs from the basic pattern of groundmass and voids. In the groundmass, a wide variety of features not related to voids such as accumulation of materials or the absence of a component, changes in shape, composition of constituents and packing can be found. Voids infilled for more than 50 percent are considered to be a feature of the groundmass. Besides the description of special features their wquantity and distribution is also given.

The next step, after the description of thin sections, is the reconstruction of the processes. Features due to one process are grouped together. For example, cutans of pure clay, argillans, and voids completely infilled with pure clay are both a result of clay illuviation. When a relatively large number of voids is completely infilled with clay, this process is more developed than when only argillans occur. The quantity of the different features and their distribution with depth give an indication of the magnitude of the process of their formation in a profile In soils, a number of processes can often be identified and when enough thin sections are examined, the magnitude of the individual processes can be indicated together with information on whether processes are active or have coccured in the past. Features formed by one process can be changed or disturbed by others.

For example, clay illuviation features can be distrubed by the fauna, and as a result fragments of these features are present, embedded in the groundmass as papules. In hthis case, it is rather easy to decide which feature came in first and which followed, and to trace the successive processes. In other cases, it is less obvious and very complicated features are to be seen as a result of different processes. One example is a root

* Features indicated with an asterix are explained in the glossary.

channel where, due to redox reactions, an accumulation of iron compounds (neoferran) is seem to be formed in the groundmass adjoining the void walls. This void became infilled with loosely packed soil material from upper horizons, after which an animal crossed this feature, leaving a void infilled with mineral excrements.

In the field of pedology and land use, a good deal of information can be gained from the micromorphological study of thin sections. This information can be grouped under four headings, viz., (i) origin of the parent material i.e. *in situ* weathered rock, sediment, colluvium, etc., (ii) exogenic processes like flooding, aeolian sand or silt deposit or erosion influencing soil development, (iii) soil forming processes - physical, chemical and biological and (iv) land use or management effects arising from basic cultivation, irrigation, drainage, burning, and such other techniques.

Methods

Thin section preparation *Techniques and Study Methods:* The samples for micromorphological study were processed to thin sections according to the method described by Jongerius and Heintzberger (1975). Using this method, samples (8 x 15 x 5 cm) of undisturbed soil material were air-dried, impregnated with plastic, hardened, sawn and ground into 15 μm thick, large sections (8 x 15 cm) mounted on glass slides. The thin sections are studied with a light microscope in plain transmitted light, under crossed polarizers and in reflected light, with magnifications up to x 250. The compositions of a limited number of samples containing amorphous microcrystalline or opaque materials are studied by a combination of scanning electron microscopy (SEM) and energy-dispersive X-ray analysis (EDXRA) on small parts of thin sections. These methods are described in Bisdom, *et al.* (1975 and 1976).

Terminology: The terminology used in these discussions is kept as simple as possible. In the first instance, the micromorphological observations are described using the terminology of Brewer (1976). In a number of cases no adquate "Brewer" terms are available and where such adequate terms were not available, new ones indicated by descriptive terms have been introduced.

In the descriptions the micromorphological observations are grouped under three headings: groundmass, voids and special features. The mineral alterations are described after the system develoepd by Stoops, *et al.* (1979). For the description of voids and void systems a sinple system is developed to characterize them at several levels. Three groups of voids are distinguished and they are: (i) voids forming a part of the structure (ii) packing voids of the basic soil constituents, and (iii) other voids present in peds or apedal soil material. Basically voids visible in thin sections have two kinds of shapes: equant or elongated. Equant voids* are those in which the ratio of short to long axis is < 0.4. Elongated voids* are those in which the ratio of short ot long axis is > 0.4. With additional information on regularity, arrangement and sizes, voids can be described adequately. Voids forming part of the structure are described as elongated, whether or not intersected. The number of voids and degree of intersection indicates the grade of structure development. In addition, the length of these voids, the regularity of the void walls, nature of intersection nodes* and inclination of ped faces can be given. Other voids present in peds or apedal soil material are also described as elongated and equant voids. Besides information concerning size and shape, the branching or interconnection of voids can also be given. The packing voids* of the basic soil constituents are not described as voids but are characterized by the kind of organization of the basic components, dealt with as coarse and fine material. The system developed by Stoops and Jongerius (1975) is used to describe the packing of the basic components. When no packing voids can be observed with a light microscope the soil material is porphyric. In Fig. 1, a survey of voids and void description terms is given. The definitions of the main terms are given in the glossary (appendix I). The essential terms, with the exception of those introduced by Brewer (1976), which are assumed to be known, are defined in the glossary.

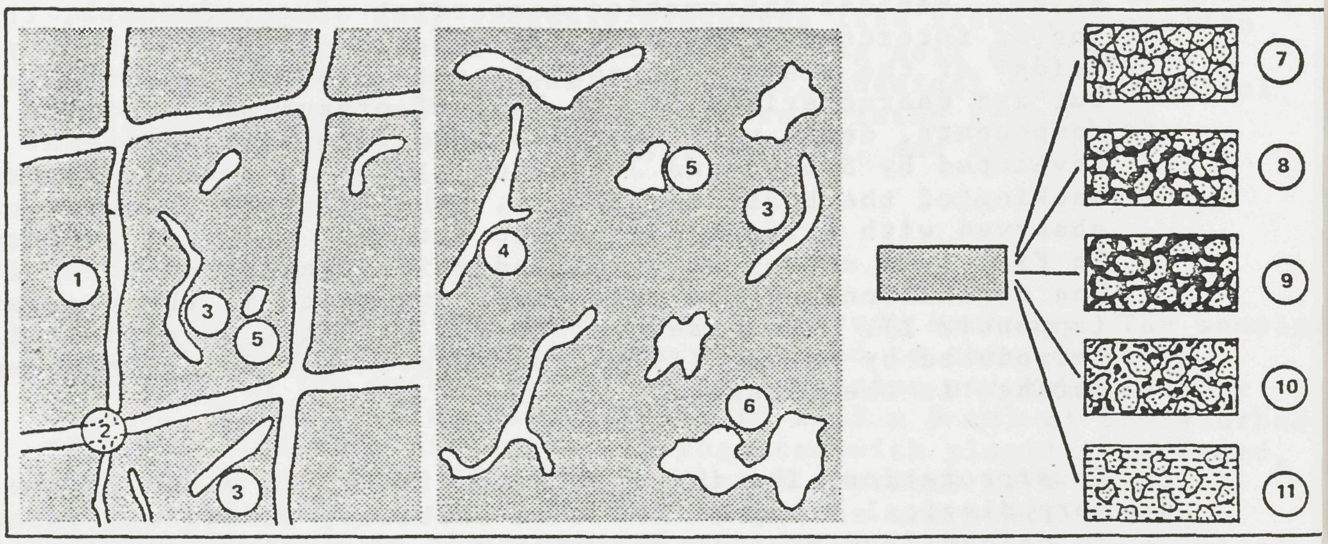
Interpretation: The interpretation is mainly based on the micromorphological study of the thin sections; additional information is gained from profile descriptions, analytical data, field study of a selected number of pedons and from the literature. The level of the interpretation varies from pedon to pedon and largely depends on the number of thin sections available and their depths. Also, the nature of the processes occurring or which have occurred influences the level of interpretation. The interpretation gives the main recognized porcesses, their occurrence, importance and whether they are current or former processes. If detected, and important for soil genesis, the orgin of the parent material is also given. The micromorphological interpretation is valid for the studied pedons. Extrapolation should be performed with care as the micromorphological variation of the features within the same series has not been studied.

MAIN PROCESSES IN BENCHMARK SOILS

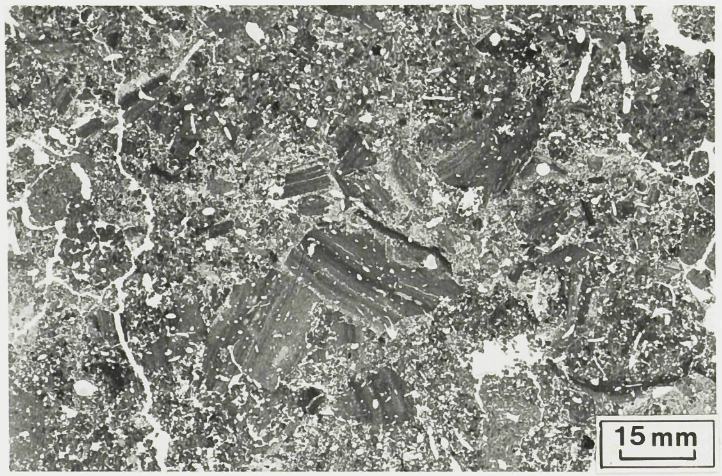
This part deals with (i) origin of the parent material, (ii) exogenic processes, (iii) soil forming processes and (iv) influence of management practices. The first two subjects are indicated briefly, the last two are dealt with in more detail.

Fig. I

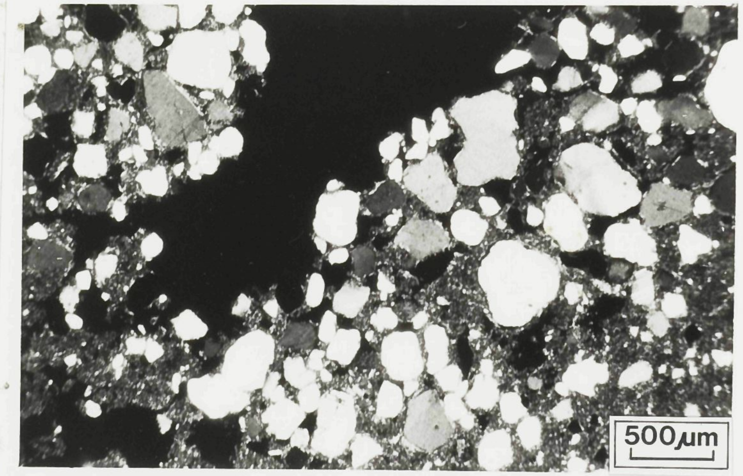
Survey of the system used for the description of voids



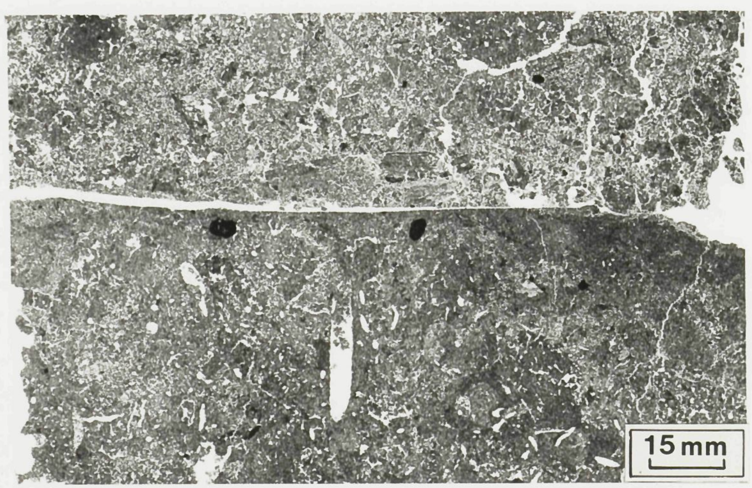
Voids belonging to the structure	Other voids	Packing (adapted from Stoops and Jongerius, 1975)
1 intersected elongated voids	3 elongated voids	7 monic c/f related distribution
2 intersection node	4 branched elongated voids	8 gefuric c/f related distribution
	5 equant voids	9 chitonic c/f related distribution
	6 interconnected equant voids	10 enaulic c/f related distribution
		11 porphyric c/f related distribution



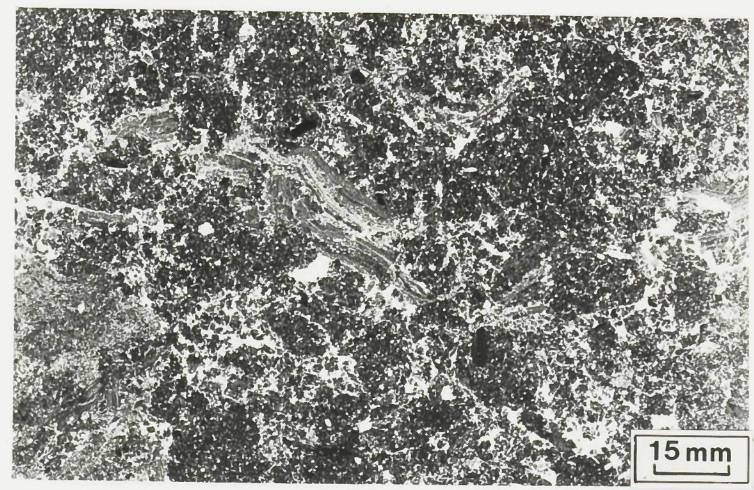
A. Fragments of a sedimentary surface deposit, embedded in the B horizon as result of management practices. Kanjli soil, ca. 45 cm depth (plain light)



B. Infilling of allochthone mineral grains embedded after swell and shrink in the groundmass. Coimbatore soil, 30 cm depth (crossed polarizers)



C. Transition Ap, A12 horizons, showing compaction and infilling of voids in the top of the A12 horizon. Zarifa viran soil, ca. 8 cm depth (plain light)



D. Embedded fragments of laminated beddings present in a mollic epipedon. Haldi soil, ca. 15 cm depth (plain light)

Fig. 2

Origin of the parent material: Soil-forming processes and influence of management practices has sometimes caused, and can still cause, considerable changes in the parent material, but in many cases the origin of this material can still be indicated.

The soils studied were developed from a large variety of parent materials such as several kinds of sediments, colluvia and autochthone weathered rock. Remnants of sedimentary laminations and beddings, and changes in texture with depth are often present in sediments. Individual laminae in sediments generally have a rather uniform composition with a more or less specific grain-size composition due to sorting. In one of the pedons studied, the increase in clay content in the B horizon was not due to clay illuviation but a result of original differences in texture of the sediment.

In colluvia, lamination can also be present but these laminae usually consist of a variety of grain-sizes. Colluvia and outwash often contain more or less rounded nodules and rock fragments.

Profiles developed on weathered rock are very variable, depending on the kind of rock and differential resistance to weathering of the constituent minerals. Rock fragments and minerals present in these soils are usually rather angular. Sometimes, zones of resistant minerals occur in the pedon. In the Channasandra pedon studied, small zones with angular quartz grains occur which are fragments of a quartz vein in the former rock.

Exogenic processes: The exogenic processes, features of which occur in the studied Benchmark soils, deal with deposition or erosion. Depositions are due to water or wind and erosion mainly due to water.

The features due to deposition concern a variety of surface sediments and the occurences of cutans and infillings. Surface sediments due to water are usually fine- extured and consist of clay-sized and silt-sized material. These surface sediments are laminated and the individual laminae are usually uniform in composition and thickness and relatively extensive. The ralated cutans and infillings consist of the same kind of materials and are also usually laminated. The cutans are best developed on the lower sides of voids. Most of these deposits from water are due to flooding occurring after the start of the monsoon or when the snow melts in the mountains. A good example of this process is present in the Kanjli soil studied (Fig.2A). Sometimes, sandy deposits are found as a result of a break through levees of a river. This is probably the origin of the voids infilled with allochthone fine sand in the studied Coimbatore Pedon (Fig. 2B).

In the soils from the north western states, especially Rajasthan and Harayana, features due to aeolean deposition are common. Silt and fine sand sized laminae occur on the surface and many voids are infilled with loosely packed sand or silt-sized material. In voids that are more or less infilled with shaped excrements, admixtures with sand or silt-sized grains, are also common. These features are observed in a number of soils, examples being Chirai, Masitawali and Thar.

Features due to deposition decrease in quantity with depth in the pedon and complete infillings become less abundant.

The occurrence of erosion can often only be concluded from features which were originally formed deeper in the pedon but are now present in the A horizon. Erosion is evident, if large numbers of argillans and infillings of prue clay, indicative of an argillic B horizon, occur in the top soil. Examples of eroded profiles with clay illuviation features in the A horizon are Vijayapura and Mrigindihi.

Soil-forming processes: In this part, the most important processes that have occurred, or are still occurring in the soils studied are discussed. They are grouped in 7 sections and deal with biological, physical and chemical processes and their combination.

Changes caused by biological processes: The influence of the flora consists of the production and modification* of voids and organic matter in the soil. Varying floral void systems are observed. If the soil has strong swell and shrink properties, most roots are found in the voids belonging to the soil structure, where they have enlarged the voids locally. Most of the soils studied are poor in organic matter. A mull humus form is present only in the soils of the Haldi series. The influence of the vegetation decreases with depth.

The influence of the fauna on soils shows far more variation. In the first place many species produce channels, forming several kinds of void systems. Faunal channels are often coated with a layer of fine-grained soil material. These coatings are the result of plastering by the soil animals. The fine-grained material, often mainly clay sized, is generally derived from excrements. These coatings are common features in sandy soil materials of the north western states and in the red and laterite soils of the southern states. In the latter case, these coatings are often mistaken for argillans. An example is given in Fig. 3A.

Animals also produce a variety of voids which, after formation, are infilled by the animals with excrements. These animals are often deposit-feeders and their excrements consist of mineral material. If the animals are selective deposit-feeders, the excrements have different compositions than the surrounding groundmass, but often the composition shows only slight differences. The voids, more or less infilled with, often shaped, excrements are not channel-like in all cases. These voids often have an irregular shape and are commonly interconnected. These zones can occupy most of the groundmass, influencing the structure. The fauna also produces some other features like isotubules and striotubules.

The influence of the fauna in the majority of the Benchmark Soils, is more pronounced in the B horizon and often continues deep in the pedon into the C horizon. The interpretation of the features sometimes causes confusion. The coatings of fine-grained soil material can be mistaken for argillans. Deposit-feeding animals do not feed only in the B horizon. In some cases, the excrements consist of material from the C horizon which give the B horizon a heterogeneous character. This occurred in the Bijaipur pedon studied. In the Channasandra pedon, excrements composed of material from the B horizon were present in the disintegrating rock of the C horizon. Animal activity can cause considerable disturbance and homigenization of features due to other processes.

In the A horizon a relatively limited number of faunal features occur. The presence of most features in the B horizon is a consequence of climate and land use. Where temperatures are high, with long periods of dryness, the animals are pressed to live deeper in the soil. The large scale use of the land for agriculture further strengthens this development.

Clay illuviation: Clay illuviation has occurred, or is still occurring, in a large number of the soils studied. The features indicative of this process vary from argillans, cutans of oriented pure clay which are often laminated, to voids completely filled with the same material. Clay illuviation features occur in all voids present but are generally best developed and most abundant in smaller voids in peds or in apedal soil material. When the clay illuviation is more developed, the number of features increase and the cutans become thicker and more voids are completely filled with pure clay. Changes in quantity and nature of features with depth indicate the magnitude of the clay illuviation.

Other processes can disturb the clay-illuviation features. The most disturbing factor is the presence of animals. Animals usually indicated as deposit-feeders not only cause translocations of clay-illuviation features but also consume soil material which includes these features. Fragments of argillans and infillings of pure clay (papules), occur embedded in the groundmass and in excrements. If clay illuviation is a current process in recent voids (also among shaped excrements containing papules), new argillans and infillings are formed. If, on the other hand, clay illuviation features are due to former processes, animals could have homogenized the groundmass to such an extent that clay illuviation features only occur in small zones not disturbed by animals.

Current clay illuviation occurs in a few studied soils, e.g. Hathiapathar (Fig. 3B). In the Gogji-Pather pedon, recent clay illuviation features also occur, but because of disturbance by man no further clay illuviation has taken place. In a large number of Benchmark soils, clay-illuviation was a former process. Examples are : Channasandra(Fig. 3C), Bhubaneswar, Chougel, Kunnamangalam, Mrigindihi, Pusaro, Trivandrum and Vijayapura. In most of these soils, animals are active and have homogenized parts of the groundmass. As animal activity is most pronounced in the B horizon where clay illuviation is also best developed, the clay illuviation features can disappear to a large extent. The Trivandrum soil has a well-developed and well-preserved clay illuviation. In the Kunnamangalam soil, animals have homogenized many of hthe clay illuviation features. Soils with voids which have coatings in the B horizon of fine-grained, often mainly clay-sized soil material as a result of animal activity can easily be mistaken for alfisols.

In fact, it is very difficult in many cases to recognize real clay illuviation features in the field. In the two soils in which the clay illuviation was not recognized, there were no coatings of fine-grained soil material due to faunal activity. Cutans visible in the field often have a different origin.

In the Jamkhandi pedon, no clay illuviation features occur but at 112 cm depth a few papules are present. These are fragments of clay illuviation, most probably derived from a greater depth, incorporated by soil animals.

Alteration of minerals and rock fragments: In thin sections many micromorphological characteristics of weathering mineral grains, rock fragments and rock can be observed. The most important characteristics are: the secondary porosity, the pattern of mineral alteration, degree of alteration and nature of secondary products (Stoops *et al.*, 1979). All kinds of alteration stages are observed. The red and laterite soils of the southern states often contain strongly altered rock fragments.

This alteration is mainly due to former processes. Current weathering is virtually negligible. In the vertisols, studied minerals and rock fragments present are fresh to strongly altered. Weathering is still occurring in these soils. In the sedimentary deposits of the northernplains, some of the minerals alter. Micas especially show varying stages of weathering and can be strongly altered. In a few soils, weathering argillans occur in packing voids and around mineral grains. Examples are the Chomu and Fatehpur soils (Fig. 3D).

Illuviation in alkali soils: Soil material with a high sodium saturation is very unstable when wet. The soil material, especially in the A horizon, is dispersed and flows into voids, causing shifting of the material. Due to the dispersion pure clay is released. In the A and B horizons, this results in the occurrence of cutans and complete infillings of voids. The cutans and infillings are composed of pure clay (argillans), clay-sized material (not argillans), silt-sized or fine sand-sized material. These features are laminated, and laminae of different compositions generally alternate (Fig. 4AB). In alkali soils, features due to this process occur on a large scale. Clay illuviation as understood for an argillic horizon, is present. Argillans and voids infilled with pure clay also occur. At the same time, however, a far greater mobility of soil material occurs and pure clay laminae are present together with other more or less fine-grained laminae. Moreover, these features are not restricted to the B horizon, but are equally present in the A horizon. Due to these clear differences with pure clay illuviation, it is justified to consider this illuviation in soils with a high sodium-saturation as a separate process.

Several processes cause disturbances in these illuviation features. The fauna can homogenize large parts of the groundmass, including these features. Due to the inflow of soil material stress occurs and deformations result. Precipitation and solution of salts also cause changes. Examples of soils in which these features are present are :Zarifa Viran, Hirapur and Sakit.

Changes caused by redox reactions: Differences in the mobility of mainly iron and manganese influenced by the redox potential (E_H) and pH are chiefly responsible for depletions and accumulations of these elements in certain zones. A variety of features are due to this process: cutans, neocutans and noduels of iron and/or manganese and grey, reduced, zones along voids or in the groundmass. In vertisols, sesquioxides (predominantly manganese are often accumulated in carbonate nodules. There are examples of these in the Achmatti and Kagalgomb pedons.

Sesquioxidic accumulations currently being formed as nodules in the groundmass have diffuse or clear external boundaries and are generally irregular. Examples are the Hathiapathar and the Itwa pedons. In the Itwa pedon, grey coloured, reduced zones occur along voids. In the field, these grey zones can be mistaken for argillans. Once formed, accumulations of sesquioxides can be very well preserved. In a number of cases sequioxidic accumulations were a result of former processes. The neosesquans present in soils developed on coastal alluvium (Dandi and Motto) were formed shortly after deposition and are inherited.

After formation, sesquioxidic nodules often have a sharper external boundary and become more regular and rounded. Homogenization of the groundmass by soil animals is the main cause of the changes in sharpness of external boundaries and in shape. Fragments of all kinds of sesquioxidic accumulations can occur embedded in the groundmass and in excrements in the same way as papules are present. Usually, the central parts of larger nodules are preserved. In the Mrigindihi soil only remnants of sesquioxidic nodules are found due to the homogenization of the soil fauna. As animal activity is most pronounced in the B horizon, changes in sharpness of the boundaries and in the shape of the nodules are greatest in this horizon. In the C horizon less changes occur. A good example of these processes is the Chougel pedon.

Sesquioxidic nodules can also be present in colluvia and outwash deposits. In these cases the nodules are rounded off and have a sharp external boundary. Large sesquioxidic nodules (>2 mm) can also be rounded due to strong swell and shrink in the surrounding groundmass.

Carbonate: It is present in many forms : cutans, neocutans, complete infillings of voids and as nodules in the groundmass. The carbonate consists of rather equant crystals of varying sizes from a few μm to 100 μm in diameter, or needle - shaped crystals (except for nodules in the groundmass). Carbonate can also be present in different quantities as small single crystals. In the groundmass or can form all fine material between mineral grains as in Chirai pedon.

Carbonates also have different occurrences with depth. In some cases an accumulation is found near the surface due to high evaporation. In others, the carbonate content increases with depth as a result of leaching. In vertisols, not only carbonate nodules are formed but carbonate can also be precipitated around rock fragments or sequioxidic nodules. In one case, the whole pedon was free of carbonates but in the C horizon, along a few voids, thick neocalcitans occurred (Haldi pedon). The presence of these carbonates is ascribed to seepage of carbonate-containing groundwater.

Carbonate nodules often show different growing phases. At one depth features due to disintegration of carbonates and to their formation can be observed. Carbonates can be precipitated in voids in disintegrating rock fragments increasing the fragmentation. Fragments of carbonate rock were also present in a few cases.

Features due to strong swell and shrink in vertisols: The structure in the studied vertisols was nearly always coarse angular blocky with inclined horizontal axes of the peds. Angular soil fragments which have split off during shrinkage often occur in voids. After swell and shrink this soil material can be present as coatings along void walls. Clay domains in the groundmass are oriented near voids and, when present, around larger mineral grains, rock fragments and nodules, resulting in a skel-vosepic or vo-skelsepic plasmic fabric. Deep in the A horizons these plasmic fabrics are often strongly developed. Features due to clay illuviation were not observed in these soils. Larger allochthone nodules and rock fragments usually have sharp external boundaries and are rounded off, largely as a consequence of the vertic properties.

Influence of management practices: Most land in India is used for agriculture, and therefore, most of the Benchmark soils are the one taken from arable land. In nearly all these soils, features due to management practices are present. These features can be grouped under two headings: viz., influence of basic cultivation practices and influence of irrigation practices.

Influence of basic cultivation practices: In medium and fine-textured arable soils the A horizon is often unstable. The high temperatures and long periods of dryness reduce the content of organic matter to a minimum. When monsoon rains start and the topsoil becomes saturated with water sorting of grain sizes can occur and some of the soil constituents flow with water, in voids. Slaking crusts are formed on the surface, and several kinds of cutans and infillings can be found in voids. The composition of the slaking crust varies but the main part is fine textured and consists of laminae which are mainly clay-sized or fine silt-sized. In many cases, these laminae alternate with each other. The same materials form the main constituents of the cutans and infillings which are also often laminated (Fig. 4C). The cutans are best developed on the lower side of the voids. The clay-rich or mainly clay-sized cutans or laminae are not argillans. The clay includes fine particles of various compositions and is not oriented. The colour is not uniform; generally dark brown, including a number of black dots. The number of cutans and infilled voids decreases with depth, but they are not often restricted to the A horizon. Embedded fragments (with random orientations) of slaking crusts and of cutans and infillings are common in the Ap horizon. They are fragmented and incorporated due to cultivation practices. As animal activity is often low in the Ap horizon, these fragments can be present for a long time and younger cutans and infillings can be superimposed on these features. When this sorting and inflow of soil material occurs on a large scale agric horizons develop.

The structure of Ap horizon is influenced by cultivation practices. The structure in the more unstable top soils with a fine or medium texture is, immediately after reworking, granular to subangular blocky with a large number of partly infilled voids with mineral grains and small soil fragments. Afterwards, the soil settles, the quantity of voids decreases and a rather massive structure often results. In the studied topsoils different phases are present. In the lower part of the Ap horizon a small zone is often present in which the soil material is compacted, the porosity is lower and existing voids are more or less infilled (Fig. 2C). This zone is due to ploughing, puddling, etc. and occurs at and just below the maximum depth reached by these practices.

Influence of irrigation practices: In the soils under irrigation features due to basic cultivation practices also occur. In a number of cases, the forming of slaking crusts, cutans and infillings due to sorting when wet are even more pronounced and occur down to great depths. In addition to these features some phenomena are due to irrigation only. Firstly, the land to be used for irrigation is often levelled. A variety of soil materials from the A and B horizons, containing a variety of unrelated features, can be present in the topsoil. This was the case with the Trivandrum soil studied. Also, a number of features characteristic of an Ap horizon can be found in the B horizon e.g. slaking crust fragments, after levelling, Secondly, the irrigation water may contain suspended matter, often clay and silt-sized which is deposited on the surface. The presence of suspended matter in irrigation water is very common in the Haldi soil studied. This soil has a stable mollic epipedon in which no slaking occurs. The embedded fragments of laminated beddings (Fig. 2D) must be ascribed to irrigation.

The quality of water can also influence processes in irrigated soils. In the Nabha soil, some carbonate precipitation is observed, predominantly in root channels in the A and at the top of the B horizon. The whole pedon, with the exception of these precipitations, is free of carbonate. This carbonate is most probably derived from irrigation water and, due to high evaporation, precipitated close to and in root channels.

Irrigation of the soil increases the moisture content, causing a higher activity of the soil fauna in the upper horizons. A number of features are disturbed and fragments are present in excrements, but void systems are also produced. Other processes are also influenced by irrigation practices e.g. redox reactions. Consequently, after the start of irrigation a new equilibrium often has to be established for processes acting in soils.

The influence caused by man needs to be mentioned. The Thekkadi pedon has a dark-coloured A horizon resembling a mollic epipedon. The dark colour is due to the presence of a large number of charcoal fragments. This charcoal was formed during burning of the forest and incorporated in the soil by high animal activity. The charcoal fragments are present in the same way as organic material occurs in a mull humus form.

THE IMPACT OF THE MICROMORPHOLOGY ON THE BENCHMARK SOILS

The micromorphological study of the Benchmark soils offered additional and new information on various topics within the scope of pedology. A survey of the main kinds of information is given below.

Analyses of a number of features visible in the field: In a large number of profile descriptions the occurrence of clay cutans is mentioned. If cutans were actually observed in thin sections, their composition consisted of pure clay (argillans), clay-sized, mainly clay-sized or clay and fine silt-sized material. The origin of the cutans was due to real clay illuviation, plastering activities of soil fauna, inflow of wet soil during monsoon rains or by irrigation and flooding of rivers. Only some of the soils in the field originally classified as alfisols had features due to real clay illuviation. In some cases other features were mistaken for cutans in the field e.g. features due to swell and shrink or redox reactions. In the first case, stress features occur in the groundmass near voids; in the second case grey-coloured, reduced, zones are present in the groundmass near voids.

Another group of features originally assumed to be mottles, nodules, rock fragments or pedorelicts had a different nature and origin when examined in thin sections. Examples are: manganese nodules which were accumulations of manganese in the outer zones of carbonates nodules; sesquioxidic nodules which were altered rock fragments.

Features not observed in the field: Features due to real clay illuviation, which were not observed in the field, were present in a few pedons. These features were numerous enough to meet the requirements for an argillic horizon. Carbonate or gypsum, not mentioned in profile descriptions, was present in some cases.

The alteration of rocks, rock fragments, the weathering of micas and other minerals, presence of weathering argillans, release of iron compounds etc. are features which cannot be traced adequately in the field and need to be studied micromorphologically.

A large number of other features present in thin sections, formed by processes important for pedology and land use, are not visible in the field and cannot be indicated in profile descriptions. Examples are: clay separations in the groundmass, stress features, changes in packing and composition and some types of laminations.

Additional information of the features and reconstruction of the processes: Not only the composition but a lot of other information about the features, whether or not visible in the field, can be given by micromorphology. This information concerns topics such as: size, shape, boundaries, location, relation to other features, abundance and disturbance. The combination of a number of features with special characteristics, together with the abundance and distribution, indicates specific processes and extent of occurrence. An indication of additional information due to micromorphological study gives the following example. In the field, the presence of carbonate is established and nodules are indicated. In chemical analyses, the content of carbonates is measured. Micromorphology adds information about where carbonates are present, in what form and whether accumulation or disintegration occurs, or whether a stable situation is present.

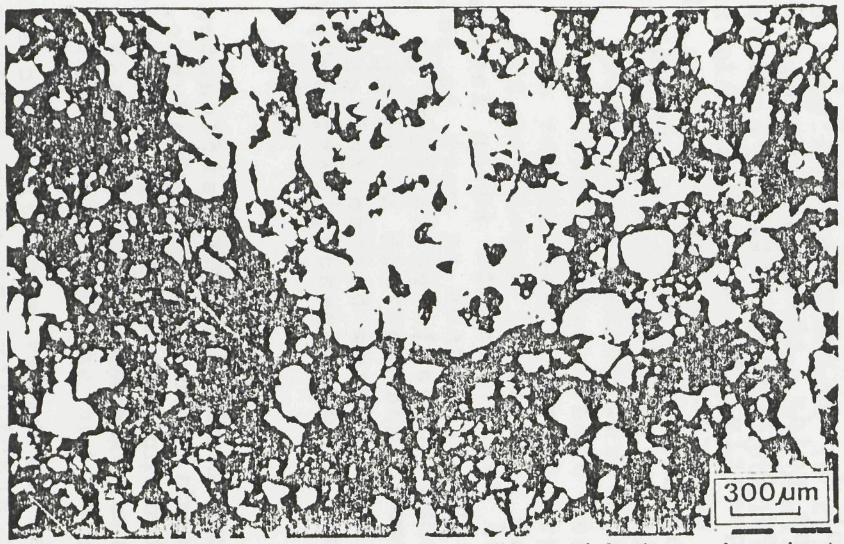
Superimposing of features and timing of processes: Superimposing of features indicates a succession of processes with time. When animals which homogenize parts of the groundmass are present, clear evidence of periodic processes, past or present, can be traced. For example, when fragments of infillings are present in excrements, and infilling of the same material is present among these excrements, the infilling is a result of a process that occurs at the same time as the animal activity. On the other hand, when fragments of infillings are present in excrements, and none of this kind of infilling occurs in the voids, this is a result of a former process, ceasing because of animal activity. Many other examples can be given. Consequently, for a number of soils not only the nature and magnitude of processes can be given, but also an indication of the time of occurrence, past or present, and the relation with other processes.

CONCLUSIONS

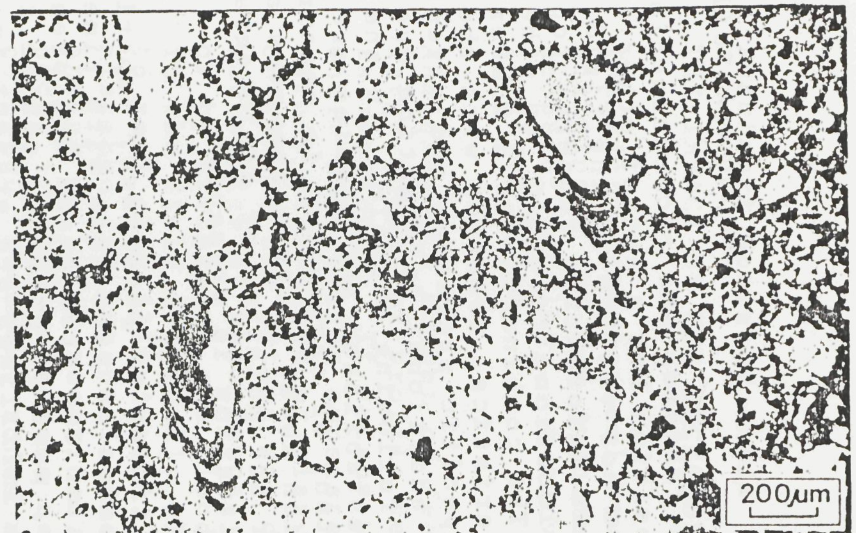
The micromorphological study of soils results in an increased understanding of past and present processes at work in soils. The nature of the parent material and a large variety of changes due to soil-forming processes and land use can be given. Not only the processes responsible for the changes but an indication of the extent of the processes and time of occurrence, past or present, can also often be detected.

The information gained is important for the classification of soils and adds new dimensions to physical and chemical analyses. Micromorphological research should be applied when clay illuviation is expected or when clay cutans are observed in the field.

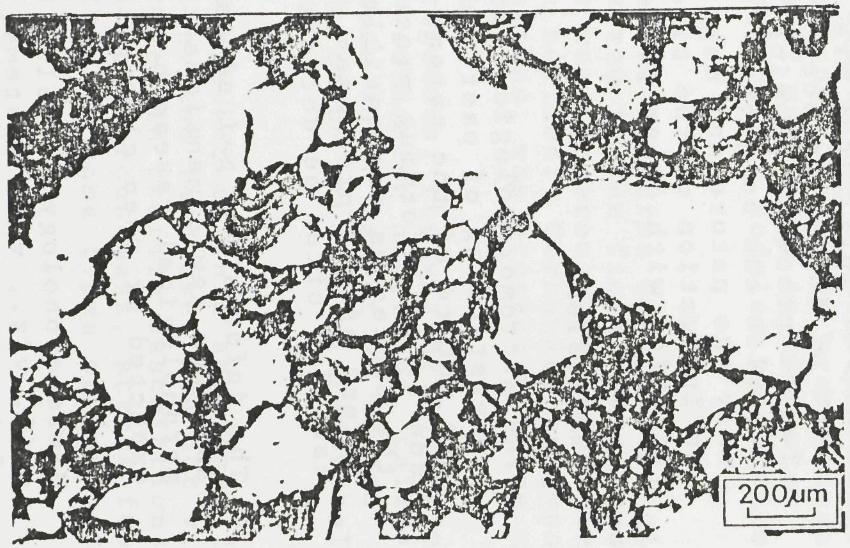
Micromorphology can also be used to study special aspects of the soil, viz., void systems, their stability and permeability, impact of irrigation on the soil and nature and extent of weathering of minerals and rock fragments.



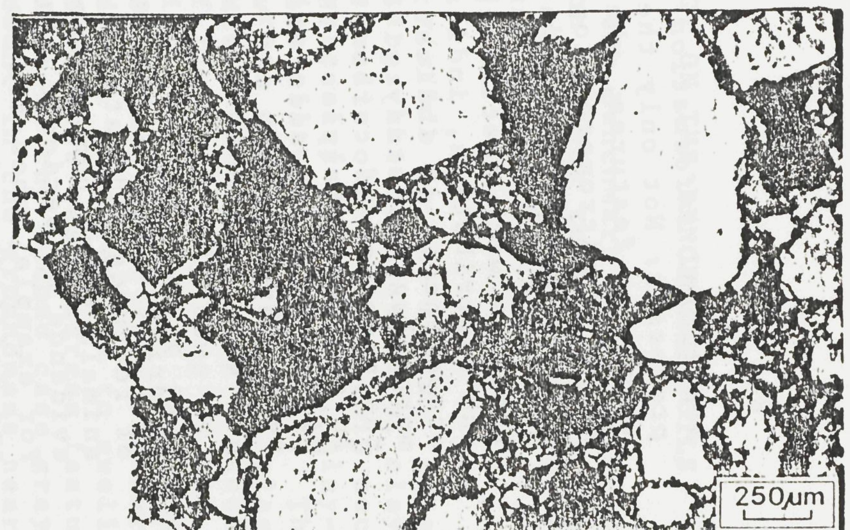
A. Void with thick coating of fine-grained soil material, due to plastering by soil animals. Vijayapura soil, B horizon (plain light)



B. Argillans and infilling of pure clay due to current clay illuviation. Hathiapathar soil, B horizon (plain light)



C. Ferri-argillans of a former clay illuviation. Channasandra soil, B horizon (plain light)



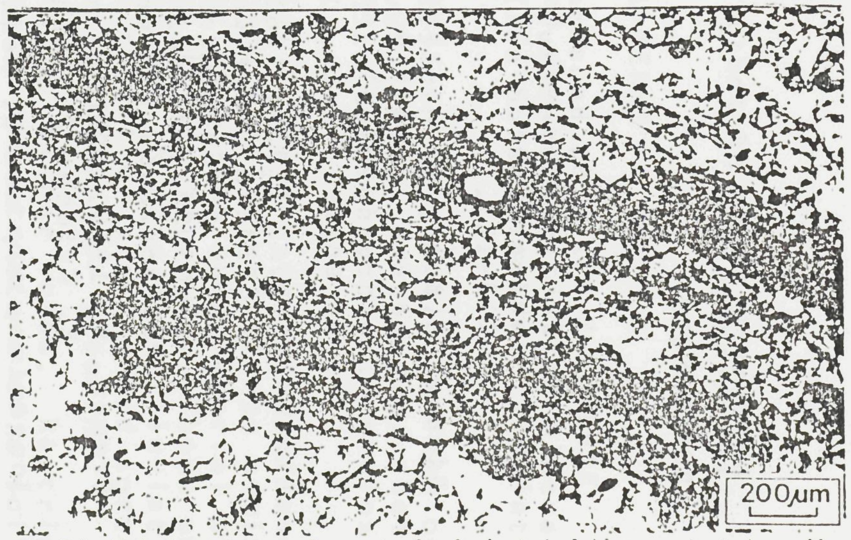
D. Ferri-argillans due to weathering. Fatehpur soil, B horizon (crossed polarizers)

Figure 3

A. Laminated infilling mainly composed of pure clay, due to inflow of dispersed soil material. Hirapur soil, B horizon (plain light)

B. Laminated infilling composed of pure clay, clay-sized material, silt and sand, due to inflow of dispersed soil material. Sakit soil, A3 to B2 horizon (plain light)

C. Laminated cutan composed of clay-sized material and sand, due to shifting in the topsoil. Basiaram soil, A horizon (plain light)



D. Embedded, turned over, fragment of a laminated slaking crust. Ladwa soil, Ap horizon (plain light)

Figure 4

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GLOSSARY OF MICROMORPHOLOGICAL TERMS

- Argillan : A cutan composed dominantly of clay minerals (Brewer, 1976), Restricted to pure clay illuviation and weathering cutans.
- Bio-geogenetic laminae or beds : Geogenetic laminae or beds composed of material of biogene origin e,g. shells, bones, excrements, peat fragments, plant remains (Kooistra, 1978).
- Cutans of clay-sized material : Cutans composed of unoriented clay minerals containing a relatively large admixture of other clay-sized materials. The same material also occurs as complete infillings of voids. These cutans and infillings are not due to pure clay illuviation but are, for example, the result of slaking and sorting of soil material, due to irrigation or flooding.
- Intersection node : Junction of planar voids. Restricted to planar voids belonging to the structure of a soil.
- Infilling/infilled void : The secondary material present in a void covers more than 50% of the surface area.
- Modification of voids : Secondary changes in the shape of original voids.
- Packing : Organization of the basic components of a material, referred to as coarse versus finer (c/f) related distribution.
  - The c/f related distribution expresses the distribution of individual particles in relation to finer material and associated voids (not included in the particles), (Stoops & Jongerius, 1975). This related distribution represents the packing of the basic components of (soil) materials.
  - Monic c/f related distribution : Only particles are of one size group or amorphous material, are present.
  - Gefuric c/f related distribution : The coarser particles are linked by braces of finer material.
  - Chitonic c/f related distribution : A skeleton of coarser particles which are wholly or partly surrounded by a cover of finer material.
  - Enaulic c/f related distribution : A skeleton of c coarser particles with aggregates of finer material in the intergranular spaces.
  - Porphyric c/f related distribution : The coarser particles occur in a dense groundmass of finer material (all c/f distributions after Stoops & Jongerius, 1975).

- Packing voids : Voids due to random packing of basic components of a material.
- Partly (in) filled voids : The secondary material present in a void covers less than 50 per cent of the surface area.
- Passage features : A pedological features consisting of soil materials. It has a tubular form and no distinct external boundary. It is the result of the single passage of an animal through wet and unconsolidated soil material. Passage features can be distinguished from the surrounding material by : differences in packing, disturbances of laminae, the presence of excrements and elongated particles oriented along the long axis of a tube (Kooistra, 1978).
- Pressure-affected zone : A pedological feature, caused by pressure on a material. These zones can be distinguished from the surrounding material by : an increased compaction, a change in orientation vis a vis the undisturbed material, e.g. deflection of elongated particles and laminae, etc.
- Structure : This term refers to the soil structure as given in profile descriptions (Soil Survery sStaff SCS, USDA, 1975).
- Submicroscopy : All work on undisturbed materials with electron microscopy, ion microscopy,,laser analyses, etc., usually done on and in thin sections of soils and weathered rocks and on and in loose, unimpregnated, materials (provisional definition by : Bisdom, Kooistra 1981).
- Texture:
  - Coarse textured : Sands, loamy sands and sandy loams with less than 18 per cent clay, and more than 65 per cent sand.
  - Medium textured : Sandy loams, loams, sandy clay loams, silt, silty clay loams and clay loams with less than 35 per cent clay and less than 65 per cent sand; the sand fraction may be as high as 82 per cent if a minimum of 18 per cent lclay is p present.
  - Fine textured : Clays, silty clays, sandy clays, clay loams and silty clay loams with more than 35 per cent clay (FAO-Unesco, 1974).
- Voids : Spaces not occupied by solid organic or inorganic materials.
  - Equant voids : Voids in which the ratio of short to long axis is $\frac{1}{2.5}$ or 0.4.

- Elongated voids : Voids in which the ratio of short to long axis is $\frac{1}{2.5}$ or o0.4
- Branched voids : Voids with lateral extentions.
- Interconnected voids : Concurrent voids of different systems except for planar voids belonging to the structure of a soil.
- Intersected voids : Crossing planar voids. Restric tricted to planar voids belonging to the structure of a soil.

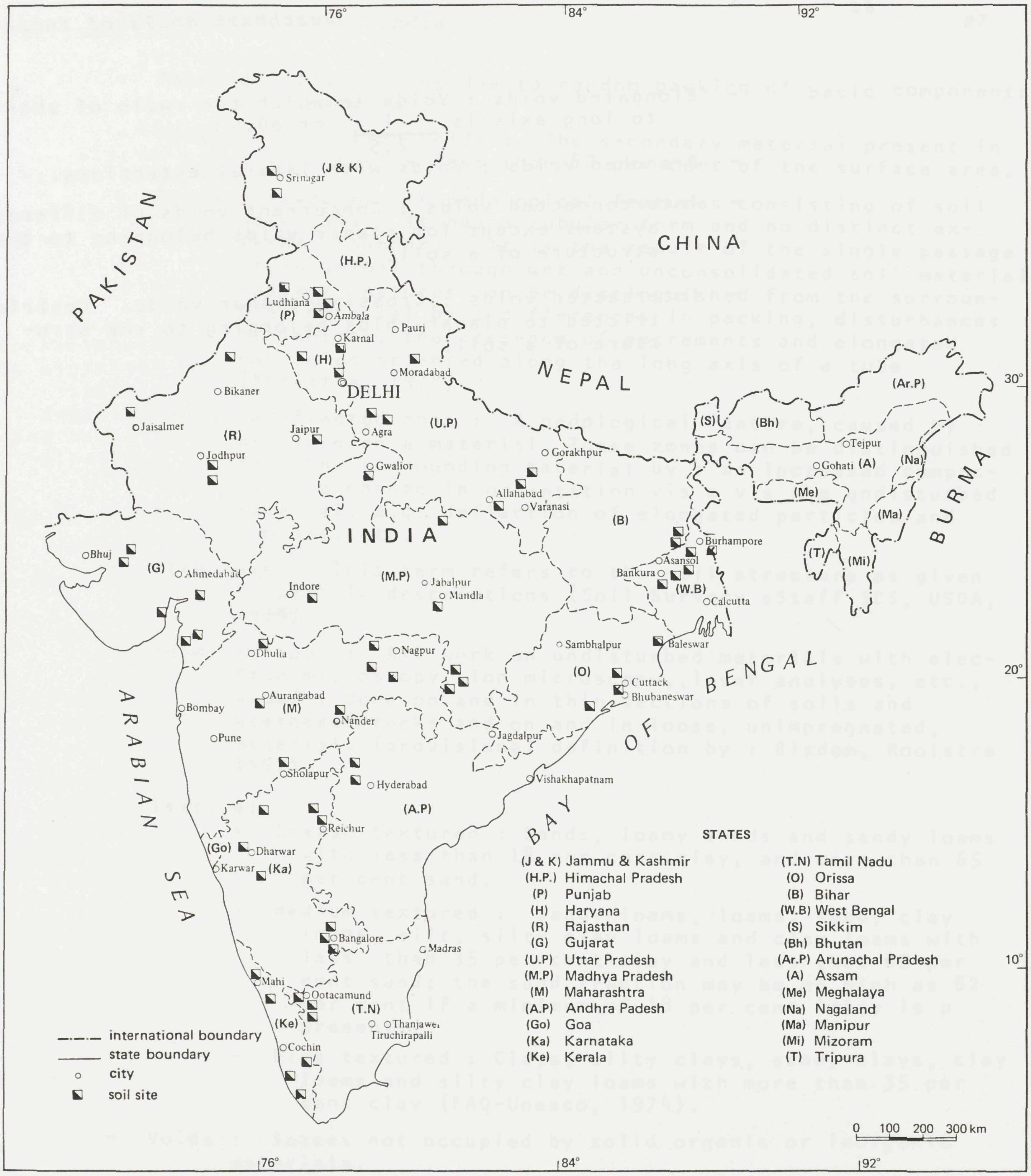

Figure 5. **Location of benchmark soil sites**

THE REFERENCE SET

The location of the Benchmark soils studied is given in Fig. 5. The Benchmark soils studied are presented in the following order:

Soils of the Kashmir Valley.

1. Gogji Pather series	-	Jammu & Kashmir
2. Wahthora series	-	Jammu & Kashmir

Soils of the Himalayan and Northern Mountains

3. Dhumakot series	-	Uttar Pradesh

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Part III containing the soils of the Desert Region (23-27) and the Soils of the Black Soil Region (28-49);

Part IV containing the soils of the Red and Laterite Soil Region (50-66) and the soils of the Coastal and Deltaic Region (67-70).

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