Classification from Landsat TM of Indurated Volcanic Materials (*tepetates*) of the Mexican Neo-volcanique Belt

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Abstract

Tepetates, altered indurated and sterile volcanic tuffs, are located among the neo-volcanic belt in central Mexico. They are divided into three classes according to the erosion level: outcrop tepetates, discontinuous tepetates (in process of erosion), and underlying tepetates (related to fragile areas with high erosion risk). For local communities and peasants, the existence of tepetates is a heavy constraint, with the impossibility to cultivate the land as it is. In order to know the localization and extension of tepetates, we experimented with various classification techniques of a Landsat Thematic Mapper satellite image. Masking techniques were used, assisted both by a DEM and photo interpretation, in addition to radiometric segmentation to obtain a map of tepetates in a study area. The resulting map showed the location of outcrop tepetates well, in agreement with existing soil maps, but underestimated underlying tepetates and high-risk erosion localities, due mainly to the heterogeneity of the classes at the scale used (30 m pixel).

Introduction

The present study follows previous research of *tepetates* in Mexico (Werner *et al*., 1988, Zebrowski, 1991; Peña and Zebrowski, 1992; Etchevers *et al*., 1992; Quantin, 1993; Hidalgo, 1995; Prat *et al*., 1996; Navaro and Prat, 1996). The objective was to demonstrate the origin, components and erosion processes of *tepetates*, as well as to define the conditions of rehabilitation for agricultural purpose (Prat *et al*., 1998).

Tepetate is a *Nahuatl* vernacular word used by Mexican farmers to name any hard layer, either outcropping or below ground level. Generaly, *tepetates* are volcanic indurated formations like tuff, or calcareous, hardened soils. Depending on origin, the characteristics and uses of *tepetates* are very different. This study focuses on *tepetates* of volcanic origin described by Dubroeucq *et al*. (1989) and Zebrowski (1991). They are compact tuff, hardened materials, with low contents of organic matter and nitrogen, and low porosity. Due to this physical and chemical sterility, these layers are unsuitable for agricultural purposes and support little natural biota.

The aim of this paper is to investigate the possibilities of using Landsat Thematic Mapper images to study the spatial distribution of *tepetates*. Using traditional classification techniques in association with masking techniques, we obtain a map of *tepetates* over the preliminary study area of the western Sierra Nevada of Mexico.

Context and objective

Tepetates are located among the neo-volcanic belt of central Mexico (fig. 1), which supports a high population density, including Mexico city (Musset, 1990). Problems and constraints linked to *tepetates* include scarcity of agricultural land, environmental protection, planning, risks of flooding and destruction.

Much work has been done in pedology and agronomy to study the possibilities and conditions for creating a new agricultural soil from the basis of *tepetates* (Quantin, 1993; 1997). The results of the breaking of the hard *tepetate* with a bulldozer, making terraces, and following simple agronomic recipes (split up fertilization, adapt crops in association, and rotation system), are very encouraging. In the first year, the *tepetate* productivity is as good as the regional productivity for most of the crops (wheat, barley, beans, ...), and corn productivity increases in the second or third year (Navarro and Zebrowski, 1992; Báez *et al*., 1996).

However, because of a high cost of development (around

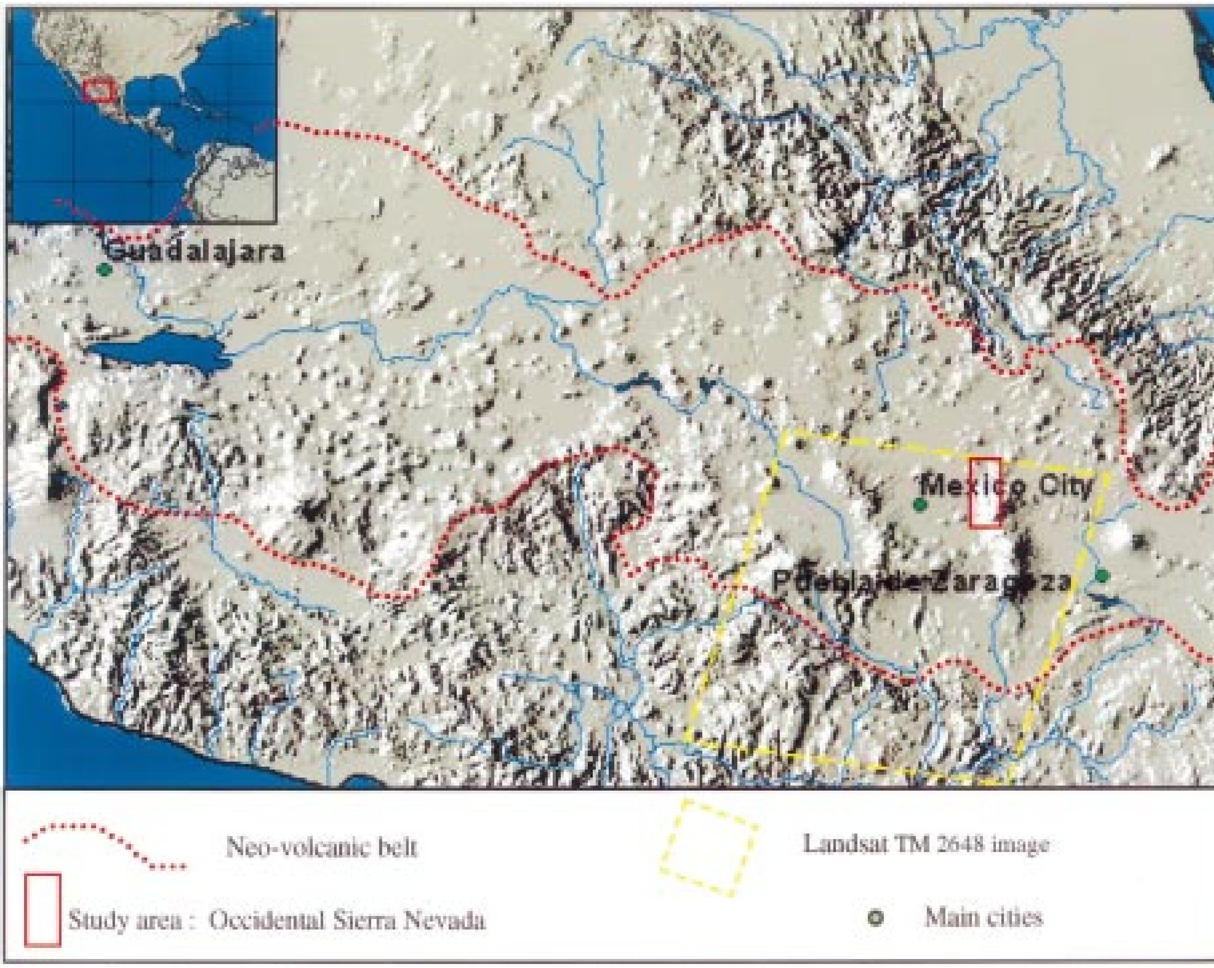

Figure 1 Location and study areas over a shaded relief map of Mexico (extracted from Esri, 1998)

1500 US$/ha), and because of the needed time to break the *tepetate* (40 hours for 1 ha) (Navaro and Prat, 1996), it is not possible to rehabilitate *tepetates* for agricultural purpose in an exhaustive way over several thousand square kilometers. To apply an effective rehabilitation program of *tepetates* for agricultural purposes, it is important to know the extension and characteristics of theses formations, as well as to estimate the real needs of the concerned farmers. Few attempts to map *tepetates* have been done: Peña and Zebrowski (1992) mapped the Occidental Sierra Nevada, and Werner *et al*. (1988), Tlaxcala State. These maps need to be extended to a larger region of the neo-volcanic belt. Peña and Zebrowski (1992) give a synthetic cartography of *tepetates* location over this region, using the interpretation of older (ea. 1980's) pedologic maps from the National Institute of Geography and Statistics (INEGI), but this work seems to be incomplete and too inaccurate for the actual application.

The objective of this study is to determinate classification criteria for *tepetates*, based on a well mapped area of *tepetates*, in order to apply the criteria over a larger region and to areas for which we do not have any data other than satellite imagery.

Location and data

We chose three different preliminary study areas around Mexico city, to compare the results (Servenay, 1997). Because of the similarity of the results, this article focuses on the most representative area.

The Landsat TM image of October 15th of 1991 (Past-Row- 26-47) contains the valleys of Mexico city, Cuernavaca, and Toluca. The study area (fig. 2) was selected according to the possible or verified presence of outcrop *tepetates*. The choice of this preliminary study area was guided by the great number of other studies already made on this area of the western Sierra Nevada (Zebrowski, 1991; Zebrowski *et al*., 1996).

Spatial characteristics of *tepetates*

Outcropped *tepetates* are rarely homogeneous (fig. 3) due to a high number of variations in the possible association between very eroded areas and non eroded areas, where *tepetates* are still covered by 10 to 80 cm of soil and vegetation. In fact the eroded areas are characterized by big spots of bare *tepetates*, while the non eroded areas are still

Figure 2 Color composite with bands 4-5-3 for the study area: the Western Sierra Nevada.

covered by a thin soil layer that hide the *tepetates*. Between these extreme states, we consider that every intermediate state is possible.

There is a weak relationship between some climatic zones and distribution of *tepetates*. These climatic zones are defined by annual rainfall, which are well correlated to altitude. Furthermore, the outcropping of *tepetates* is heavily conditioned by slopes. When vegetation has disappeared, the resulting bare surfaces can cover up to several hectares, and are extremely susceptible to erosion (gullies can reach sizes up to 30 m!). Every high rainstorm accelerates the degradation, and generates floods down stream.

We divided the general *tepetate* theme into three distinct classes that take into account the notion of the outcropping proportion of *tepetates* in relation with the presence or absence of covering soil (fig. 4). Theses three classes are referred as "outcrop *tepetates*", "discontinuous *tepetates*" and "underlying *tepetates*". Outcrop *tepetates* are baren of soil and vegetation. Discontinuous *tepetates* join together heterogeneous areas: they are made of an association of distinct spots (fig. 3) more or less extended on ground level (a few square meters), each spot being made of either outcrop *tepetate*, soil, or vegetation. Underlying *tepetates* are not visible because they are still completely covered with original soil, often with some vegetation.

Methodology: process and classification steps (fig 5)

The image was geometrically corrected by taking into account a DEM with a precision of 90 m. Several band combinations and processing techniques have been tested, in order to produce the most appropriate color composite images and indexes.

Figure 3 Field photographs showing outcrop tepetate, discountinuous tepetate mixed with rest of soil and straggly herbaceous vegetation, and underlying tepetate under bigger sheet of soil in way of erosion.

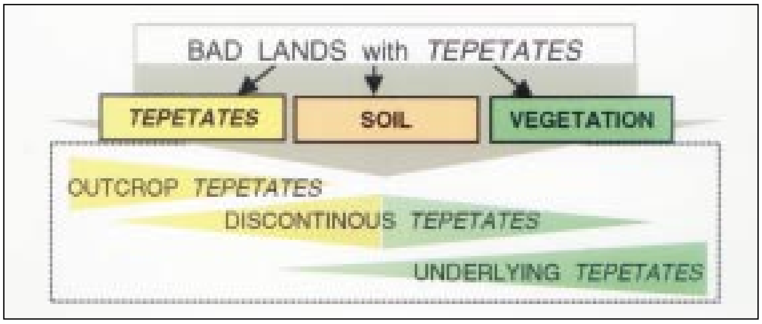

Figure 4 Tepetates' typology according to the spatial organization of its components

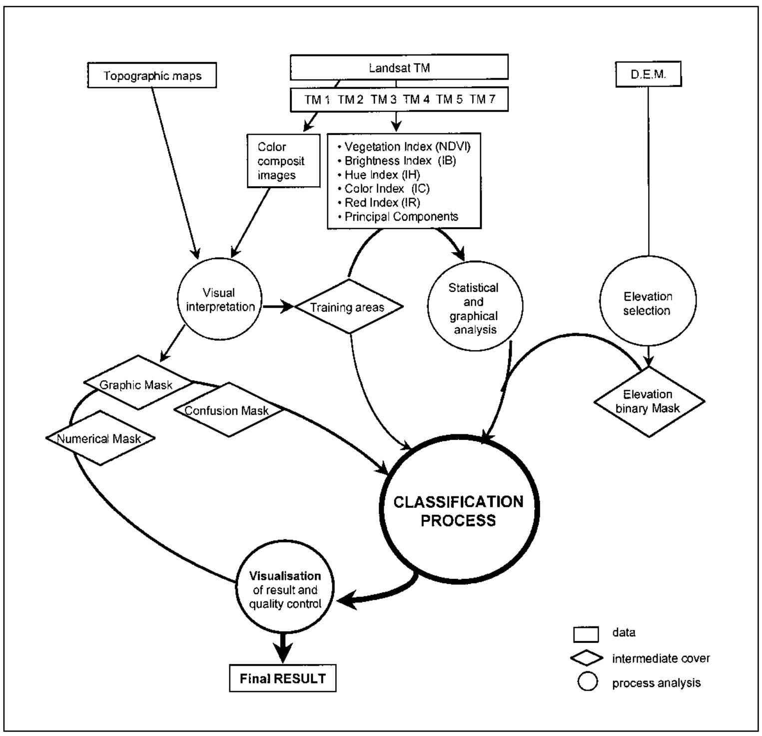

Figure 5 Classification steps

An altitude mask was created from the DEM to take away the *tepetate* signature that could appear in areas higher than 3000 m. This altitude boundary corresponds to our general criteria for theoretically existing *tepetates* in and around the valley of Mexico City. The boundary corresponds also to a annual rainfall of 900 mm. The dry season at this high altitude is shorter and weaker than in lower altitude areas. Volcanic tuffs, from which *tepetates* come from, cannot exist in their indurated form under such humid condition.

Two color composite images have been produced by combining bands 4, 3 and 2, according to R-G-B visual tool, and bands 4, 5 and 3. These color composite images are best for detection of details around mineral-rich areas, including *tepetates*, quarries and urban zones. The color composite images are used to select training zones and also to create graphic masks. The graphic masks are used to discriminate mineral themes that are radiometricaly too close to *tepetates* but are easily identified. Training zones were taken on every known theme.

The index bands created were:

the normalized vegetation index: NDVI= NiR-R/NiR+R

the brightness index: $BI=[(TM1^2+TM2^2+TM3^2)/3]^{1/2}$ (Mathieu, 1998)

the hue index: HI = (2*TM3-TM2-TM1)/(TM2-TM1) (Escadafal *et al*., 1994)

the color index: CI = (TM3-TM2)/(TM3+TM2) (Escadafal and Huete, 1991)

the reddish index: $RI = TM3^2/(TM1*TM2^3)$ (Madeira *et al*., 1997)

the first three components of the principal component analysis (PCA) based on bands 1, 2, 3, 4, 5, and 7

Bands and indices have been used to calculate statistics over training areas. After a graphical analysis of these statistics for each training zone in each theme (fig 6 and 7), we have been able to select the best bands and indices for the classification process: band 5 (TM5), brightness index (BI), color index (CI) and reddish index (RI). Furthermore, according to the statistics, we can identify which themes will be easy to discriminate. Using data these way, we know it is not possible to completely discriminate themes like urban zones from outcrop *tepetates*.

The supervised classification used the previously selected bands and indices. A simple radiometric segmentation classification was insufficient to accurately separate *tepetates* from urban regions, so we introduced a spatial discrimination method using masks.

Using topographic maps, our knowledge of the field, and the photo interpretation of color composite images we drew boundaries of every urban area that could be confused with *tepetates*. Using the same data, agricultural areas were also extracted, because *tepetates* can be confused with plowed fields. Using these two masks we started a first classification by dynamic clustering of clusters where we set the number to 3 (Ball and Hall, 1965).

Even using masks, some areas of outcrop *tepetates* and scattered houses or small villages were misclassified. We then created a graphical mask by drawing boundaries around misclassified areas. We executed a new classification only over the misclassified pixels.

Using successive classifiction results over integrated masks we could improve the final results according to what we knew, and could distinguish the three different classes of *tepetates*: "outcrop *tepetates*", "discontinuous *tepetates*", and "underlying *tepetates*".

Results and discussion

In the final classification over the study area (690 000 ha, the three themes of interest had the following areas:

Outcrop *tepetates*:	690 ha (1%)
Discontinuous *tepetates*:	4 500 ha (7%)
Underlying *tepetates*:	8 200 ha (13%)

Using bands and index bands to classify the image by radiometric segmentation, we obtained good discrimination between *tepetates* and similar soils. However, there was poor radiometrical discrimination between *tepetates* and urban areas, mainly due to brightness and heterogeneity of materials used for construction of building. By introducing mask techniques, we have been able to enhance our previous results.

Discontinuities and heterogeneity inside the same global *tepetates* class, and particularly inside what we called "discontinuous *tepetates*", are not necessarily distinguishable directly with satellite data like those we have used. However, even with a 30 meters pixel, it is possible with good field knowledge over the study area, to extract part of these mixed surfaces.

Figure 8 shows our final results. We can see that outcrop *tepetates* have a very peculiar spatial distribution. On the piedmont eroded areas of outcrop *tepetates* have shapes of tongues. They are located over the combs and some plain areas, often between two ravines. The tenths of the tongues correspond to local topography. We can also see that every piedmont is not necessarily involved in the degradation of *tepetates*.

In the final result, only the "outcrop *tepetates*" theme appears to be verified in terms of extension and distribution in the Occidental Sierra Nevada region compared to the inventory work over *tepetates* realized by Peña and Zebrowski in 1992. The "discontinuous *tepetates* theme seems to be too heterogeneous for good classification results using 30 meters pixel data, due to the number of possible associations between soil, vegetation and *tepetates*. The attempt to reduce these confusions results in the underestimation of this class. The "underlying *tepetates*" are also underestimated, due to the confusion between vegetation and soil layers that completely hide these *tepetates*. Using higher resolution data could reduce these rough estimations in mixed areas.

Because the area concerned is large and located in fragile and marginal zones from a human and natural point of view, it is important to continue this investigation[1] to provide an effective method for mapping the whole mexican neo-volcanic belt region.

Conclusions

Tepetates of the neo-volcanic belt of Mexico occur under certain conditions: volcanic origin (surge or pyroclastic flow), low annual rain fall with a marked dry season (at least 5 months), altitude from 2500 to 3000 m, and slopes greater than 10%. They can be divided into three classes according to their erosion level: outcrop, discontinuous, and underlying *tepetates*. Because of increasing pressures on the land, it is desirable to inventory the location of *tepetates* and their states of degradation, before selecting areas for rehabilitation.

Over a preliminary study area of the western Sierra Nevada, we experimented with classification techniques, and applied them to the detection of *tepetates*, using a Landsat TM image of 1991. The utilized method consisted in the use of several indices (brightness, color and reddish) in addition to band 5, to discriminate *tepetates* from other classes. In addition to this radiometric discrimination, we used masking techniques to further limit the classes.

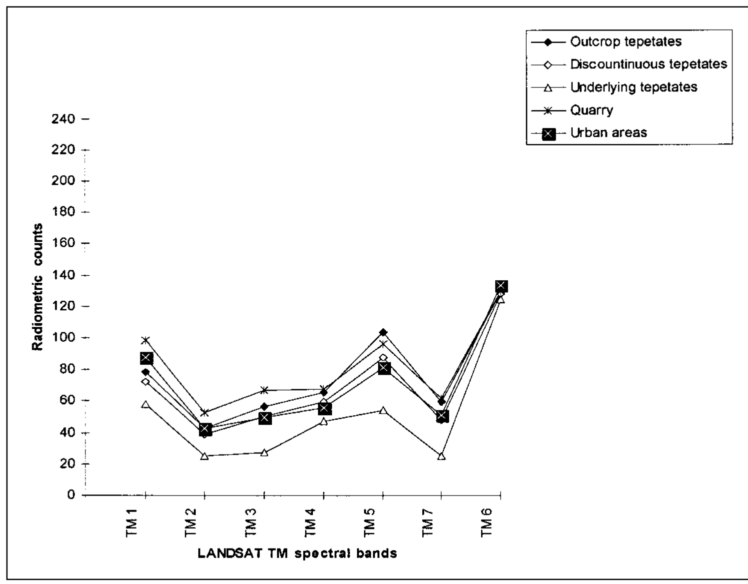

Figure 6 Spectral signature of related mineral surfaces around tepetates for Landsat TM

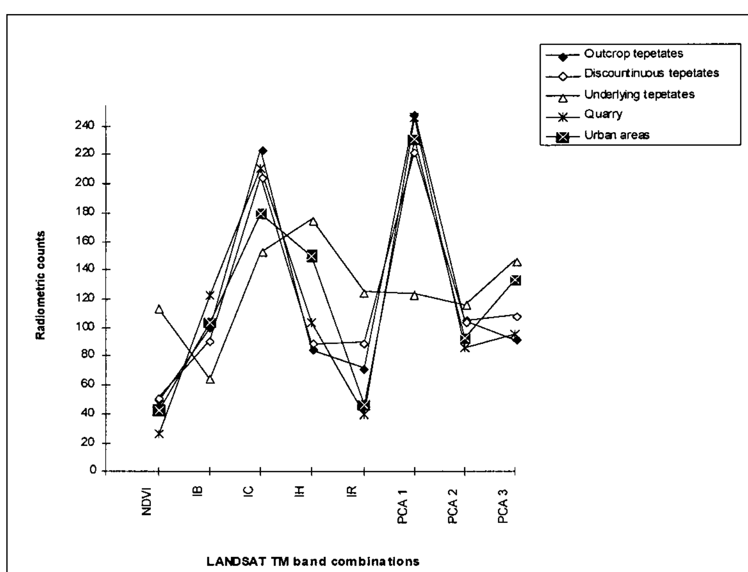

Figure 7 Spectral signature of mineral surfaces around tepetates for indices and principal component analysis

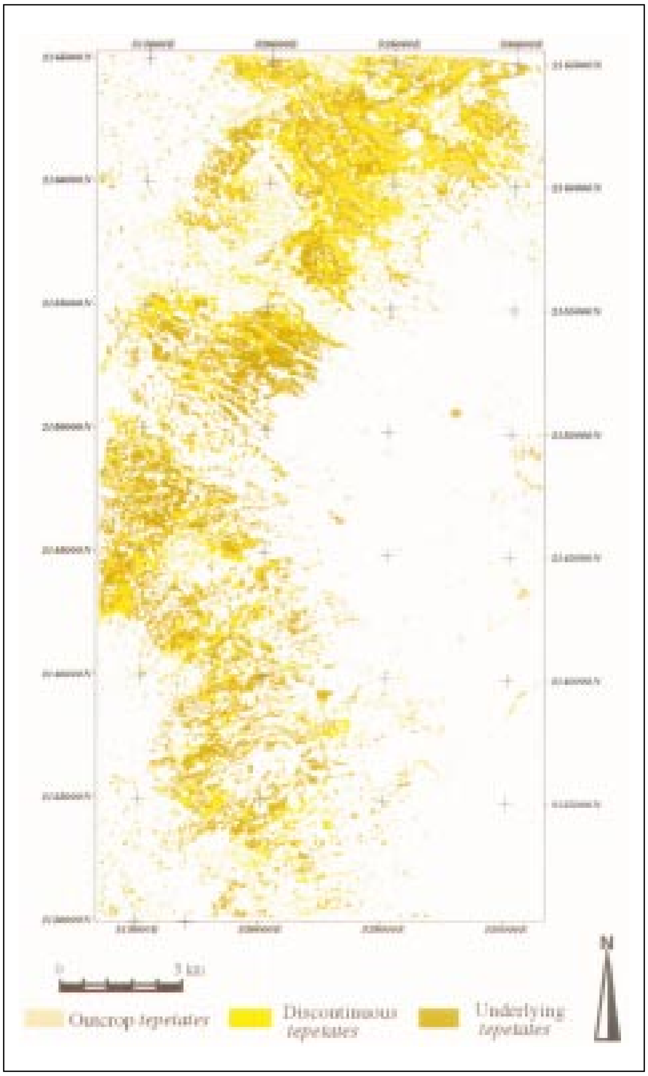

Figure 8 Classification results

Only the outcrop *tepetate* theme is easily classified, while discontinuous and underlying *tepetates* are underestimated due to the heterogeneity of the classes at the scale used (30 meter pixel). The results show that Landsat TM sensors allow for the detection of outcrop *tepetates* as long as we employ techniques like masking to avoid radiometric confusion with urban areas. However, detection of *tepetates* in other regions may use different criteria .

Our classification was validated by a comparison with the previous work done on the field the same year as the acquisition date of the utilized image.

To extend this work we need to define more precisely the landscape units of the neo-volcanic belt attached to *tepetates*, and obtain a general map of these global units with NOAA AVHRR satellite data. Once these units are defined, other ancillary data will be assessed over representative study areas, to find a way to define more accurately the boundaries of outcropped *tepetates.*

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