# GEOLOGICAL MAPPING IN DENSELY ANTHROPISED ZONES. METHODOLOGICAL APPROACH.

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The geological cartography of an area included in the natural zone of expansion of the town of Barcelona has served us to test some specific methodological aspects for geological mapping in urban areas built on alluvial sediments. Apart from direct observation-based methodologies, indirect methods including interpretation of old series of aerial photographs and topographic maps, subsurface methods, historiographic research and especially the interpretation of high resolution Digital Elevation Models (DEM's), have been used here quite successfully. The results are that the geological map of the quadrangle number 392-2-2 of the Geological Map of Catalonia on a scale of 1:25,000 accomplishes the standards planned for the global project, and that the acquired experience will be of great help in mapping urban areas with nearly 100% of anthropic cover.

## INTRODUCTION

In densely anthropised zones and more especially in urban areas, the geological substratum holds a heavy overburden imposed by human activities. Urban and surrounding areas are involved in continuous processes of modification which result in a deeper and deeper interaction between the human activities and the geological substratum. Moreover, most towns in Europe are located on alluvial plains, and therefore, they are built on geologically complex and vulnerable structures. Detailed knowledge of the geological constitution of such areas is essential for their development and to prevent natural risks (Berástegui and De Gans, eds., 1997). Similar projects pursuing this goal are in progress in most of the Geological Surveys in Europe.

The best tool the geologists have to summarise the geological constitution of an area is the geological map (Maltman, 1990; Puigdefàbregas, 1997). From a geological mapping point of view, urban and densely anthropised areas, and alluvial plains, have a common attribute: they are characterised by poorly and very shallow exposures. Thus, classical, direct observation-based methodologies (Lahee, 1961; Barnes, 1991; McClay, 1987) only allow for partial cartography, and their results in such areas remain restricted to a location of the outcrops on poorly accurate morphologic maps, something less than bi-dimensional maps. In order to transform these partial maps into complete documents, thus giving information in the three ordinary dimensions, and to present a final geological map fitting with the standards of the general project, urban geologists must use specific methodologies.

The aim of this paper is to present the methodology used in the cartography of a quadrangle of the Geological Map of Catalunya on a scale of 1:25,000 (Berástegui and


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Losantos, 1994 and 1996; Losantos, Berástegui and Saula, 1996) located on a highly anthropised area, and its final results.

## GEOLOGICAL SETTING

The study area is included within the perimeter of the quadrangle number 392-2-2 (Sabadell) of the Geological Map of Catalunya on a scale of 1/25.000. It lies north of Barcelona, on a NE-SW trending depression (called the Vallès-Penedès) bounded to the NW by a major extensional fault (Figure 1). From Miocene to Recent times, the Vallès-Penedès depression evolved as a halfgraben basin in the extensional tectonic regime which affected the Western Mediterranean during the Neogene. Internally it is structured by a NE-SW trending system of extensional faults, cut by a younger NW-SE trending system of extensional faults. The Neogene and Quaternary infilling consist of continental alluvial sequences, including some minor shallow marine and transitional successions. Key papers are: Fontboté (1954), Anadón et al., (1979), Cabrera (1979), Cabrera (1981-a and b), Fontboté et al. (1990); Agustí et al. (1990), Cabrera and Calvet (1990), Cabrera et al. (1991), Roca and Guimerà (1992), Bartrina et al. (1992), Roca (1992), Garcés (1995) and Berástegui et al. (1996).

The Middle to Late Miocene alluvial-fan deposits in the study area display a wide variety of facies assemblages, ranging from proximal to distal-marginal zones deposits, organised as stacked units, displaying a mostly aggradational pattern. The minor marine sequences record the transgressive highstand and regressive stages of a major transgression which affected the Catalan continental margin during Langhian (Middle Miocene) times. The Messinian (Late Miocene) sea-level drop which affected the whole Mediterranean is recorded in this region by noticeable erosive surfaces. In neighbouring zones, these sediments are overlain by Early Pliocene fluvial and marine deposits. During Pliocene times the area was uplifted. This fact and the successive glacio-eustatic Late Pliocene to Holocene sea-level changes controlled the evolution of the regional drainage network. The Latest Pliocene-Earliest Pleistocene and Holocene deposits show a staircase pattern and were laid down in successively entrenched alluvial fan plains and fluvial valleys.

## DEMOGRAPHIC FRAMEWORK

The quadrangle number 392-2-2 is located in the "Sabadell-Terrassa urban corridor" (500,000 inhabitants). Archaeological research shows that the area was inhabited since the Late Palaeolithic. Mixed farming in areas of the Vallès depression is documented since Neolithic times. From 2$^{nd}$ Century BC until 6$^{th}$ Century AC, the Roman population inhabited lonely villas (*centuriae*). This life-style was maintained with little changes until 9$^{th}$-10$^{th}$ Centuries, when the first centres of population started their development (A. Martin, personal communication). Such centres of population slowly developed from Late Middle- to Modern Ages, starting their modern industrial progress towards the second half of the 19$^{th}$ Century. With the Industrial Revolution (late decades of the 19$^{th}$ Century and early decades of the 20$^{th}$ Century), and later on, with the massive immigrations during the decades of 1950's and 1960's, the area experienced a dramatic increase in population. At present 50% of the land is occupied by towns, residential areas, factories, landfills, communication infrastructures and areas of diverse using, making it opaque to the direct observation of the geological features (Figure 2). Thus, classical geological mapping techniques only allow for a partial cartography in one half of the territory.

## METHODOLOGY

The constraints imposed by the increasing development of human activity, together with geologic constraints, namely the apparent low lithological contrast between adjacent materials, the absence of regional markers and the tectonic structuration in blocks, make the physical correlation between adjacent cartographic units an intricate piece of work. Both groups impose a very specific mapping methodology which basically consists of:

USE OF DIVERSE TOPOGRAPHIC BASES OF DIFFERENT DATES AND SCALES
The scale 1:10,000 (1988) used for field work in the early phases of the project proved to be too small. It was successfully substituted by the scale 1:5,000 (1987). Other very useful bases were old topographic maps on scales of 1:25,000 (1918-1922) and 1:10,000 (1970). These maps, when compared to the most recent cartography, give information about human modifications, mainly landfills and excavations, and are of a great help in interpreting or reconstructing some masked geological elements.

USE OF AERIAL PHOTOGRAPHY
It is very important to have available the most recent aerial photographs (1:22,000-scale, year 1984; ortofotomaps at 1:5,000-scale, year 1988, and 1:25,000-scale, years 1992 and 1994) but, as in the aforementioned case of the maps, also the oldest ones are of capital importance. In the study area, the oldest available flights were from years 1956 (on a scale approximate of 1:33,000) and 1977 (on a scale of 1:18,000). Despite their minor scale, the 1954 photographs were the most useful in the interpretation of areas currently masked or covered by human activities. In particular, their study was of a great importance for mapping the Quaternary fluvial terraces and alluvial fans, as well as the pre-Quaternary basement which actually cropped out in the interfluves. The projection of the interpreted data on a topographic base of a similar age is an essential step. This has proven to be of a great help in identifying what features are natural forms or result from human activities.

HISTORIOGRAPHIC RESEARCH
Apart from the usual consulting of the existing geological literature and maps, an important aspect to be checked is the origin of the construction stones used in the oldest (Middle Ages) buildings. Historiographic research allowed to the location of the old quarries which furnished those materials, at present buried below landfills and modern buildings. This, combined with the lithology of the construction stones, gave "virtual" outcrops of some conspicuous key beds mapped in outcrops outside the study area.

DETAILED BIOSTRATIGRAPHIC RESEARCH
Although all of the outcropping materials in the study area are continental sediments, several sites have furnished very rich fossil mammal assemblages, especially microvertebrates, but also macrovertebrates (horses, elephants, hippopotamus and others). The biostratigraphic data have been tied to the magnetostratigraphic scales where available (Garcés, 1995).

SUBSURFACE METHODS
For shallow levels (from ground level to some 100 metres depth) we have used the information included in the waterwell database of the Geological Survey of Catalonia and data from public and private works, mainly foundations, tunnelling and communication routes. For levels deeper than 100 metres, seismic-reflection profiles furnished by oil exploration companies have been of a great help in interpreting the structure of the top of the pre-Neogene basement and the stratigraphy of the oldest Miocene sedimentary infilling.

USE OF DIGITAL ELEVATION MODELS (DEM's)

The most important effect of DEM's in geological cartography is that they remove the vegetal cover and most of the man-made constructions. This allows the geologist to interpret geological features in poorly exposed or covered areas. By combining three DEM derived surfaces, namely slope, aspect and flow direction, an image can be obtained which may be interpreted in the similar terms as a "horizontal" shallow seismic-reflection profile (Figure 3). DEM's in geological cartography must be used as integrated into the global iterative process which characterises the general methodology for geological mapping, and never as a separate or self-consistent tool. In the study area, DEM's have been proven to be very useful in identifying and locating the original drainage network below the towns of Sabadell and Terrassa, in defining the geometry and boundaries of the Quaternary alluvial fans and fluvial terraces, and for the location of two extensional faults. Further details on the use of DEM's in geological mapping can be found in Cirés et al., this volume.

## RESULTS

The final output obtained by using the aforementioned combined integrative approach is the sheet number 392-2-2 (Sabadell), one of the 301 forming the Geological Map of Catalunya at 1/25.000, and the first one in the project covering a densely populated area (Figure 4). The final map represents the geological features of the area prior to the strong anthropic modification (so in fact, prior to the industrial revolution of the late 19$^{th}$-early 20$^{th}$ Centuries). On a complementary map (Figure 5) the man-made modifications, both "constructive" and "destructive" have been plotted.

The main geological results can be summarised as follows:

NEOGENE SEDIMENTS:

Five cartographic units have been individualised. They are genetic units, differentiated by their lithological compositions (and subsequently from their sediment-source areas). Each unit corresponds to an alluvial system. Because of intrinsic problems derived from the own mapped area, and in particular the physical continuity of the outcrops and the tectonic structuration, the definition of cartographic units with a sequential signification (i.e. related to the dynamics of expansion-retraction-lateral displacement of the alluvial systems) has not been possible. This, which could be solved by a systematic use of very detailed bio- and magnetostratigraphic methodologies, stands quite a long way from what we realise a general geological map is. From the palaeontologic and biostratigraphic points of view, the geological map in the quadrangle number 392-2-2 is also very important, as it includes one of the stratotypical sections of the so-called Vallesian (Agustí, 1988). This is one of the Late Miocene mammal-ages currently used with a widespread acceptance in Eurasia and Northern Africa. The Vallesian was defined in the Vallès-Penedès basin to designate a peculiar assemblage of fossil mammal faunas characterised by the first entry of *Hipparion* (Crusafont, 1950). Traditionally it has been proposed that the Vallesian can be formalised as a continental chronostratigraphic stage useful for wide Eurasian and North African regions. It must be emphasised that the definition of the Vallesian as a continental chronostratigraphic stage largely depends on the existence of an accurate lithostratigraphic cartography, providing a suitable support for the ongoing magnetostratigraphic and biostratigraphic studies.

QUATERNARY SEDIMENTS:
Eight cartographic units defined as alostratigraphic units (NACSN, 1983) have been individualised in the Quaternary sediments. They can be grouped in three main types:
a/ Alluvial-fan systems of two orders of magnitude. (Hm. to Km).
b/ Fluvial systems consisting of terrace deposits entrenched at various levels.
c/ An intermediate unit (Qt3) consisting of terrace deposits and two coalescing alluvial-fans which distally evolve to a braided plain.

GENERAL TECTONIC STRUCTURE IN THE SUBSURFACE (BASEMENT AND FAULTING):
It has been basically inferred from the available industrial seismic reflection profiles. The biostratigraphic and magnetostratigraphic data have been of a capital importance to evaluate the displacements of the faults involving Miocene sediments. The interpretation of the DEM has revealed as a very useful technique in identifying subtle, non outcropping or masked tectonic structures, especially the two recent extensional faults bounding the Qt3 braided plain to the SE.

EXTENT OF THE ANTHROPIC ACTION
It consists of the identification of the anthropically modified areas, both concerning the generation of positive relief, landfills and the destruction of the relief by means of extractive activities and construction of communication infrastructures (Figure 5).

## BENEFITS

The quadrangle number 392-2-2 includes one of the areas which are experiencing the highest demographic and industrial expansion of Barcelona (4,000,000 inhabitants). This is well illustrated by comparing the most recent maps (Figure 2) with the maps of land uses for the future decades (Figure 6). It is important to note that, as the Urban Planning and Map of Land Uses (DGC-ICC, 1996) displays, in few years only a 35% of the territory included within the perimeter of this quadrangle will be accessible to direct geological observations.

The geological information included in the sheet 392-2-2 and adjacent, either on scales of 1:25,000 or 1:10,000, is important in considering its applications for territorial planning, superficial and groundwater management, environment and geologic risk. Concerning educational and cultural benefits, the occurrence of thick, continuous Middle Miocene to Recent sequences including rich fossil-mammal assemblages, in particular a stratotypical section of the Late Miocene stage Vallesian, provide an additional interest to this map, as it can help to ensure the geological heritage.

To conclude, the characteristics of the area included in the perimeter of the quadrangle 392-2-2 make an excellent natural laboratory to test the methodology just described above. Thus, the acquired experience will be of great help in mapping areas with some 90% of anthropic cover, as the neighbouring town of Barcelona (Figure 7).

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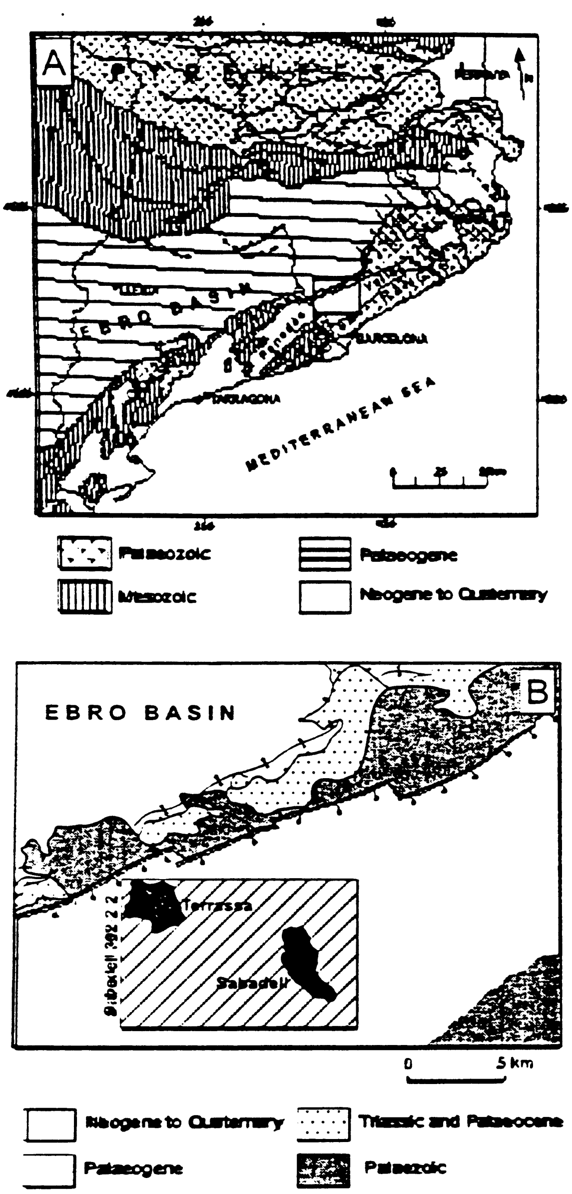


Figure 1. A. Structural sketch-map of Catalonia. B. Location of the study area.

Figure 2. Ortofotomap of the quadrangle 392-2-2.

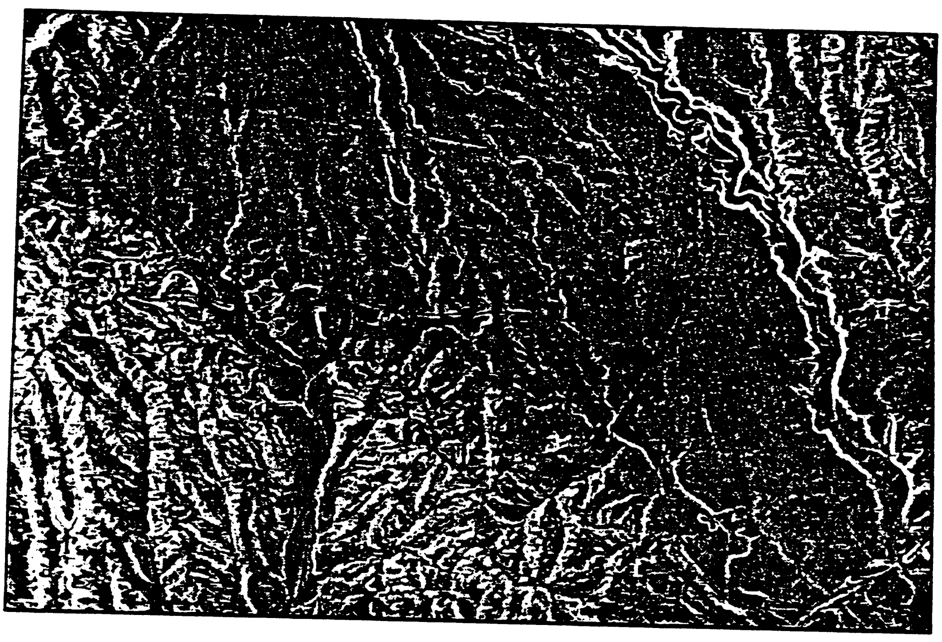

Figure 3. Digital Elevation Model of the quadrangle 392-2-2. Combination of slope, aspect and flow surfaces.

Sabadell 392-2-2 (72-30)

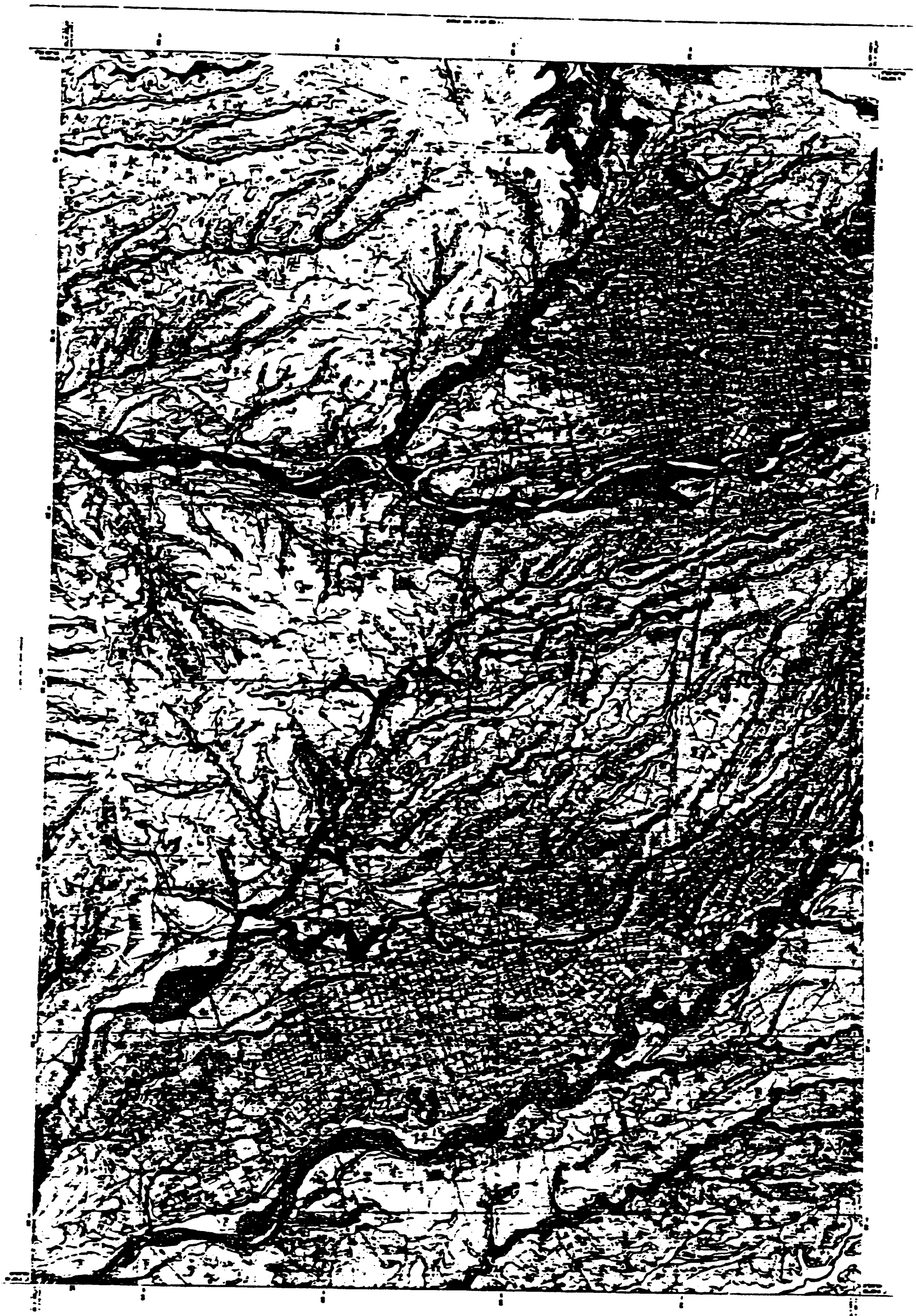

Figure 4. Geological map of the quadrangle 392-2-2.

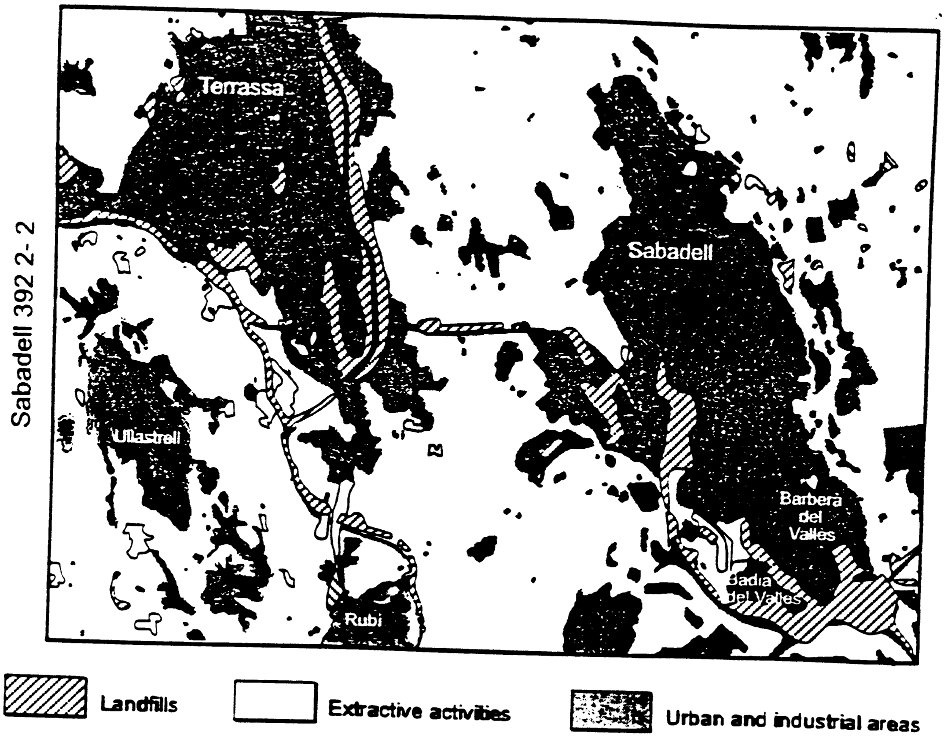


Figure 5. Areas modified by anthropic activities.

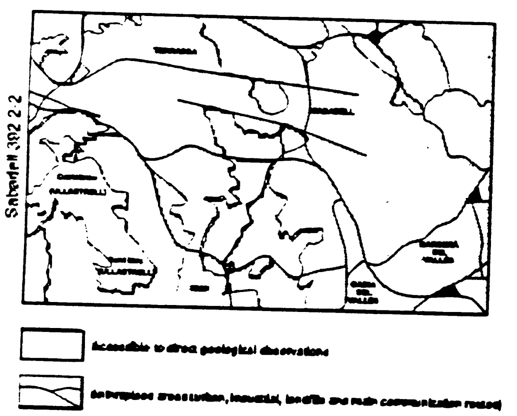


Figure 6. Areas which will be modified by anthropic activities in next few years.

Figure 7. Ortofotomap of the quadrangle 421-1-2 (Barcelona).