DISSOLUTION MINING AND ENVIRONMENTAL EFFECTS IN POLANCO (CANTABRIA – SPAIN)

Jesús Gómez de las Heras and José A. Rivadeneira de Vega

Spanish Geological and Mining Technological Institute (ITGE)
Ríos Rosas, 23
28003 Madrid, Spain
Phone: +34 91 3495700

PRESENTATION

The present report involves a part of the works carried out by the *Instituto Tecnológico Geominero de España (ITGE)* with relation to the Agreement of Collaboration with the *Centro de Investigación del Medio Ambiente (CIMA)* of the County Council Offices of Cantabria. The general title is "Research on the geological risks derived from the exploitation of brines at Polanco (Cantabria)".

Throughout this report, we would like to thank the company SOLVAY QUÍMICA S.L. for having provided the ITGE's technicians with all the information involved in attaining successfully the targets of the research.

GEOGRAPHICAL SETTING

Polanco, with a total of 3,693 inhabitants, is geographically located between the two most important cities in Cantabria: Santander and Torrelavega. The Bay of Biscay is 7 km north of Polanco.

GEOLOGICAL SETTING

In Figure 1 is shown a cross-section (modified MAGNA) NW-SE of the geological setting in the zone, where Polanco is located. With respect to the geological cartography (E. 1:10 000), we can say that in Polanco, stratigraphically speaking, there have been found Triassic (facies Keuper), Jurassic, and Cretaceous materials, as well as four different levels of Pleistocene terraces.

The Triassic facies of Keuper is composed essentially of halite, including red clays, gypsum, anhydrite and sheets of foetid black bitter spars. The stratigraphical distribution of these lithofacies is chaotic, which does not allow to correlate lithological areas, not even in boreholes nearby. This may imply that this facies has suffered strong internal strains due to the plastic and rheological behaviour of the saltern matrix faced to the tectonic stresses. Its strength, in the axis of the core of the anticline of Polanco is estimated to be over 1,700 m.

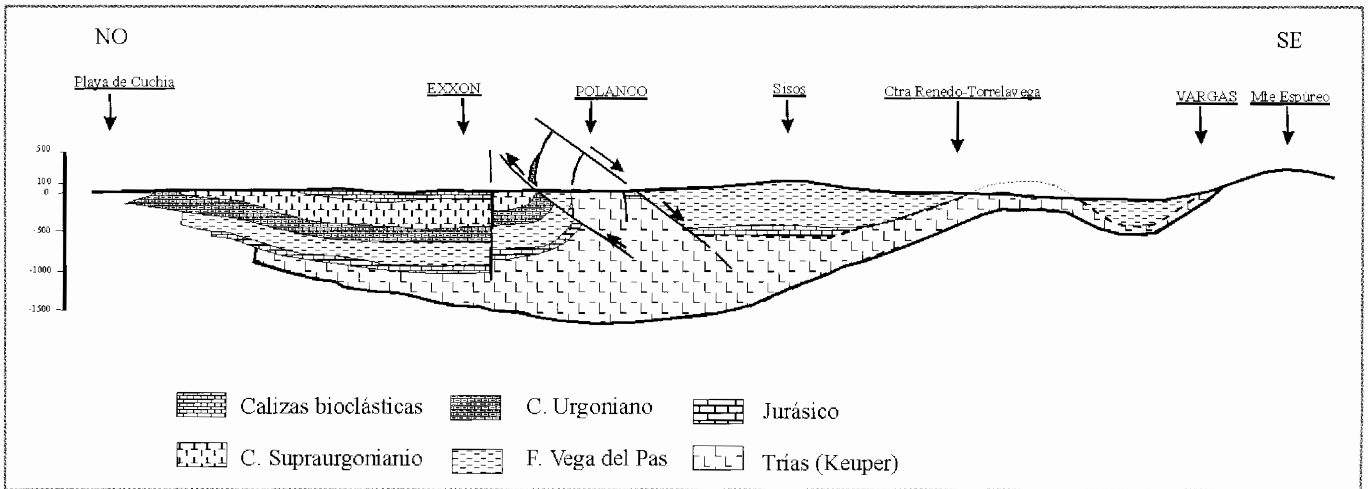

Figure 1. Geological cross section.

The Jurassic materials in the area of Polanco correspond exclusively to Early Black Jura (Hettangian – Sinemurian), and they are basically carbonated. Their strength is ranging from 180 m to 200 m.

Discordant over the Jurassic deposits, there are also materials from Early Cretaceous, and the following lithological groups can be distinguished:

Vega de Pas' Formation (Hauterivian – Barremian), composed mainly of grey, red and greenish clays, and small levels of lignites. The most part of Polanco' urban centre is located there. Its strength is estimated 400 – 500 m.

Urgonian Complex (Aptian – Early Albian). It is carbonated with outstanding debris of orbiculoidea, corals, ostreids, gastropods, etc. The total strength of this complex is estimated in 300 m.

Supraurgonian Complex (Early Albian– Middle Cenomanian). Composed of grey clays, packsands, thin levels of arenaceous limestones and lignites. Its strength is 200 m.

Finally, within the Late Cretaceous two different lithological groups can be distinguished; the first one corresponds to Middle – Early Cenomanian bioclastic limestones and the other to Turonian – Coniacian clayey limestones and marls.

In Figure 2 is shown a estratigraphical column representing the southern limb of the Anticline in Polanco (exploitation zone) built according to the information obtained from the boreholes.

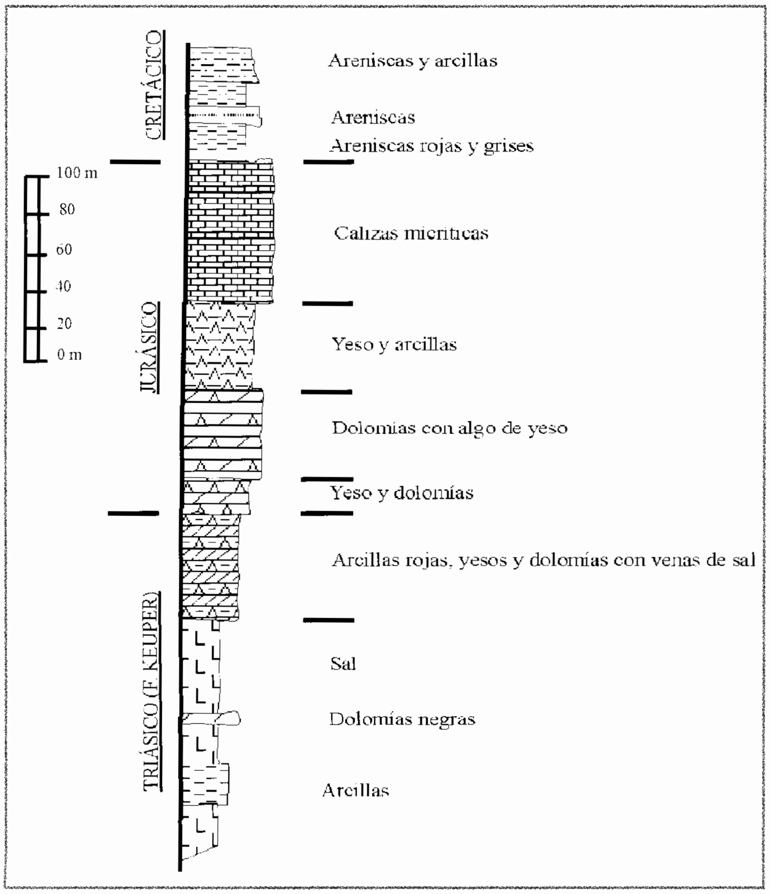

Figure 2. Stratigraphic section south anticline limb.

From the point of view of its structure, the Anticline of Polanco is a 4 km long - 0.75 km wide structure oriented NE-SW. In the northern limb, the layers are in a vertical plane (sometimes slightly inverted) being affected by a high angle reverse fault, Puente Arce's Fault. This fault is oriented NE-SW, with downthrow ranging from 50 to 100 m next to the diapir, although it seems higher when going further to NE.

The southern limb is a diapir collapse ordinary fault, Rumoroso's Fault, located beyond the folding. Throughout the data obtained from the boreholes it has been possible to measure an ordinary maximum downthrow of about 400 m in the fault. It is oriented N 60º E, parallel to the southern limb of the anticline.

Among the materials of the Supraurgonian Complex and the Cenomanian bioclastic limestone, it is considered the existence of an ordinary fault (Bao´s Fault).

At the edge NE of the diapir, there is a series of small longitudinal faults with orientation ranging from NNW-SSE to NNE-SSW, in a vertical plane and possibly with a certain ordinary component which affects slightly the eastern finishing of the structure.

EXPLOITATION PROGRESS

Although SOLVAY's company located at Barreda, an urban centre near Torrelavega, started working officially in 1908, the borehole's department had already begun to manufacture brine on 2nd August 1907. The delivery of brine to the company started on 5th August, lasting 9 hours 20 minutes for a total of 70 m^3. Nowadays, the brine supply required is 15 000 m^3/day.

From the beginning of the exploitation up to nowadays, the methodology and drilling and exploitation techniques have progressed substantially according to four different stages: the first and second stages between 1904 and 1940; the third stage between 1940-1958 and the fourth one from 1958 up to the present.

The main differences among these stages refer to:

- The method and borehole drilling techniques (176 drilled boreholes).
- The techniques used for salt dissolution.
- The techniques applied to the design and monitoring of progress in exploitation chambers and protection of the top.
- Control techniques after the exploitation.

For the two first stages, the dissolution process evolution and the progress of chambers may be defined as chaotic, because there is not any kind of control, due to the lack of techniques and tools "ad hoc".

The third stage represented the first step towards the control of the top of the chambers. However, the method used, air injection, was limited due to the high tension that had to be supported inside the chamber.

In the fourth stage, the control of the chamber was carried out by means of heavy oil. The exploitation takes place at upward stretches, but not at fixed top.

Until 1964, the method used for the process control of setting up dissolution chambers was only based on some forecasts that referred to the tonnes to be extracted and to the chambers' radios. Thé amount of tonnes of salt extracted per day was monitored.

Since 1964, the chamber's geometry control and the possibility of measure its volume during the dissolution process has been carried out by means of two different kinds of echo sounding devices: omnidirectional and directional.

Finally, the exploitation sector has been progressing in spacing towards the S-SE of Polanco. The boreholes, with more than 1000 metres deep, get into the Keuper's salt formation from 600-700 m, after having crossed the Early Cretaceous and the Jurassic.

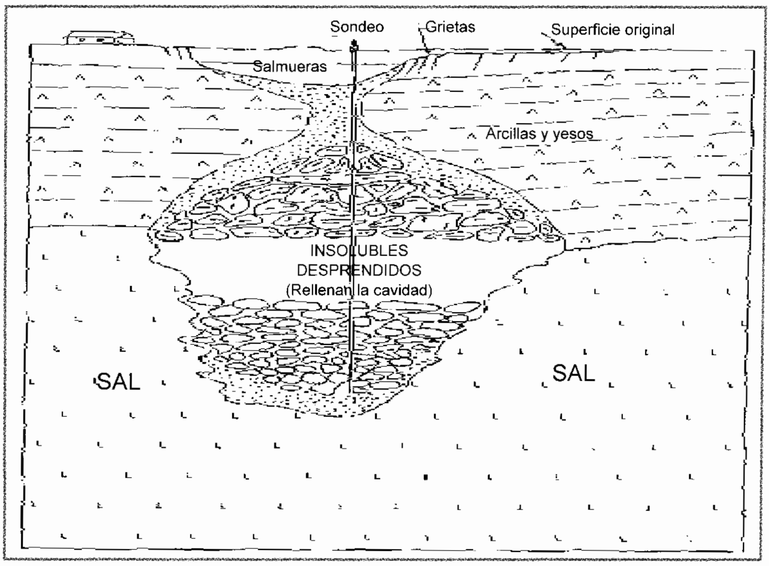

Figure 3. Schematic final cavity morphology and surface effect (Johnson, 1995).

ENVIRONMENTAL EFFECTS OF THE EXPLOITATION

The effects of mining works on surface, with the subsequent existence of a deep hollow, have a wide range of variety according to the exploitation conditions and to the geological characteristics of the site.

In the so-called diapiric structure of Polanco, the company SOLVAY has obtained saturated brine from the salt levels throughout the dissolution method since 1907. The salt levels, with different strength and percentage in halite, are located in the facies Keuper of this diapir. The first borehole, a percussion drilling in 1904, was 531.25 m deep and exploited between 155 and 531 m.

The specific characteristics of this method, along with the absence of any tool or technique that served to establish a strict control of the exploitation, at least until 1964, implied that:

The chamber's geometry was unknown.

In the exploitation phase, even during the drilling phase, the nearby boreholes chambers are communicated. The distance between boreholes was initially between 30 and 40 m. At present, it is 150 m.

There are continuous destabilizations at the top of the chambers with its subsequent fall out of control during the exploitation phase as well as once the borehole is abandoned.

The evolution towards the surface, of the same exploitation as of the falls out of control have implied and indeed imply negative effects on surface and, with different levels of intensity, can be considered as progressive changes in its morphology: craking, shears and land subsidence.

The subsidence on surface at its highest level is the collapse and the subsequent hollow (subsidence crater). The collapse is the result of a fast increase, in certain areas, of the general subsidence at the exploitation site. In Figure 3 is shown a scheme of the final configuration of a hollow and its incidence on surface (Figure taken from Johnson, 1955).

With reference to the environmental effects, most of the annual land subsidences measured within the period 1965-1998 as well as the collapses, the last one took place in 1990 to the west of the exploitation site, are located in the geological area of facies Keuper. All the collapses are linked to boreholes drilled and exploited between 1904 and 1958.

From the 14 collapses (craters) produced up to 1990, 7 are full of water and the rest of them contain different kind of materials. One of these craters has been recently authorised for its use as a deposit of inert wastes coming from the company SOLVAY.

The dimensions of the craters full of water have developed gradually according to the typical scheme of depth decrease and surface increase.

The negative effects on to the land surface up to 1964 are foreseen to continue and it is quite sure that there will be new ones in the areas already exploited, as well as in those areas being exploited at the moment and in those planned to be exploited.

Therefore, SOLVAY, aware of the necessity to foresee, control and minimise, when possible, such effects, decided to set up in November 1964 a network of subsidence control landmarks, take periodically all the data about subsidences and make the required analysis.

As far as general research is concerned, the ITGE developed the works required to establish some risk criteria as the basis to carry out land zoning and, whenever the case, define the land uses. And all this, by means of the information obtained from SOLVAY, as a starting point for the levelling campaigns, and the information supplied about the present and future negative effects on surface and on the structures located there, due to the brine exploitation at Polanco.

As a matter of information, the number of data dealt with during the works (those supplied by SOLVAY + those generated by the ITGE) has been over 10 000.

EVOLUTION OF THE SUBSIDENCE CONTROL NETWORK

The first subsidence control network was set up in November 1964 and composed of 29 landmarks, with more than 3 fixed landmarks. At present, this network has 280 landmarks plus 3 fixed landmarks, different from the initial ones.

The network has developed gradually according to the exploitation progress. Between 1964 – 1979, it was linked basically to the southern area next to the most important subsidences, located in the same zone of diapirs.

PROGRESS OF SUBSIDENCES AND TRENDS

The first work carried out that tended to establish some criteria of risks was the subsidence evolution analysis of 177 landmarks chosen among the 280 landmarks of the present network, for the period 1987-1998 (twelve years). This selection was based on: immediacy to buildings and motorways, surrounding of subsidence craters and of certain boreholes in exploitation (those located in the most external perimeter of the present exploitation site).

Thus, from this analysis, it can be concluded that:

- The zones with most subsidence are located at both sides of the S-451 motorway, facies Keuper and subsidence areas surrounding.
- Most subsidences within the period 1965-1998 are located in the landmarks next to the subsidence craters, in the facies Keuper (landmark n. 2470: 1445.3 mm, and landmark n. 1640: 1239.8 mm).
- In 1992 there was an important and global increase in the subsidence data, which is consequent with the change in January the same year of landmark (n. 3000, a fixed landmark since 1964 that got damaged by the subsidence, for another one, n. 4000, located outside the damaged geographic site).

In these 117 landmarks, it was estimated the subsidence trend through the adjustment by minimum squares. With this, it was obtained the line that shows the subsidence trend for every landmark.

Having the position of the landmarks subsidence data, with relation to their trend line, it has been zoned the exploitation site in four different areas:

- Upwards (↑), higher subsidences data than in the trend, and located under the line.
- Downwards (↓), lower subsidences data than in the trend, and located over the line.
- The same as in the trend (=), the subsidence data are on the line.
- Disgressive (ß), subsidence data of difficult interpretation due to the existence of positive measures (the landmark goes up instead of falling down).

Based on the examined information about subsidence and trends, one could consider the possibility of defining the criteria and areas of risk. However, it is utterly impossible, from the technical viewpoint, to make such definition, which would be anyway merely subjective, because what had been done so far did not point out any objective or technically supported parameter to carry out the zoning. Therefore, and with the objective information at disposal, it was opted to carry it out through the final subsidence crater analysis (1998).

FINAL SUBSIDENCE CRATER ANALYSIS

The objective of this analysis is merely to obtain the final subsidence crater and determine in consequence, at least, the parameter concerning the gradients. This target will be achieved throughout the initial subsidence crater in 1965 and the successive integration into it of the subsidence data of the landmarks located every year at the exploitation site. And all this is due to the absence of planimetrical data that could produce horizontal displacements.

The analysis was developed, initially, knowing that the task presented three disadvantages from the beginning:

- The exploitation site had suffered a subsidence very difficult to quantify before 1964, when the first control network was set up.
- The annual subsidence data taken from every new landmark did not take into account the previous subsidence occurred during the period between November 1964 and that particular moment.
- Eventually, there have been changes in fixed landmarks' location.

1st Stage of the analysis

The first step was to generate the initial subsidence crater from the subsidence data taken during the 1st levelling campaign, 07.65 (Figure 4).

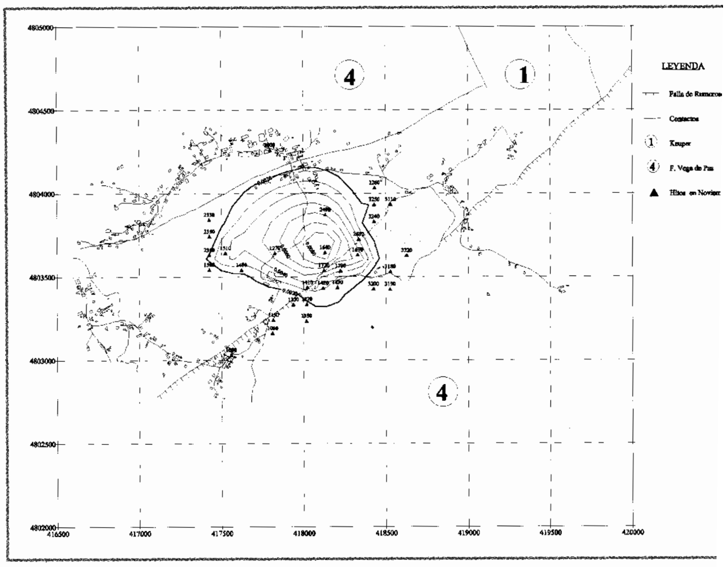

Figure 4. Initial sinkhole (July 1965).

The second step was to locate on this initial crater the landmarks set in July 1965. With this, it was possible to get for every new landmark its subsidence data previously to the origin. According to this, the subsidence crater corresponding to 1966 would be generated by adding to the data taken for every landmark during the levelling campaign of that year, the data corresponding to the subsidence previously to the origin.

Example: in landmark n. 1650 is measured a subsidence of 10.7 mm during the levelling campaign in 1966, because it had a previous subsidence of 7 mm according to its location in the initial crater in 1965. Its total subsidence with respect to the origin would be 17.7 m.

With this mechanism was generated the subsidence crater in July 1966.

By following this methodology it was believed that the total subsidences suffered by the landmarks with respect to the origin, in 1964, might be known so to achieve to generate the final crater in July 1998 (period 1965 – 1998).

Unfortunately, the methodology could only be applied when the subsidence data were not very high, and there was a moment when they increased considerably, as it occurred during the levelling campaign in November 1978, in which the maximum subsidence was produced in landmark n. 2470, with 584 mm.

By generating the subsidence crater in 1978, it was pointed out that, when drawing the isosubsidence lines, in landmark n. 2000, taken as a fixed landmark form the beginning of the levelling campaigns, there was a subsidence of 40 mm. This fact, which could have been theoretically true, was in total disagree with reality, because this landmark was located at Polanco's church and, as it was confirmed later, there was no negative sign of subsidence right there.

Likewise, in landmarks located near houses built up in the 60s, there would have to be previous subsidences of 70 and 80 mm. This would imply that there would have been certain damages, but there is no evidence about it.

Thus, it was concluded that the previous subsidences assigned to every landmark were higher than those really suffered. On the other hand, and once analysed the problem, it was considered that its origin was due to the fact that the algorithm used by the programme generator of the isosubsidence lines did not take into account that the subsidence phenomena - in this case it has a chaotic/erratic development as far as its spatial distribution is concerned - did not affect equally to the whole land surface. The area next to the boreholes is more damaged than those areas located a little bit further, with substantially lower subsidence data.

If this methodology had still been followed, there would have been, in July 1998, landmarks and zones with utterly unreal subsidences in the final subsidence crater at the exploitation site.

2nd Stage of the analysis

The wrong results obtained from the application of the methodology of the previous stage obliged to leave out such way of treatment and it was decided to make the subsidence analysis based on the individual information on the annual craters.

From the comparative analysis of the thirty craters generated as a result of the partial subsidences suffered by the control landmarks within the period 1965-1998, it is to point out that the zones with absolute greatest subsidence are located:

- on both sides of S-451 roadway, between the subsidence craters full of water.
- from 1982, also in the western area of the exploitation site, near the already existent craters.

The results of this analysis, as far as the zones with maximum subsidence and annual gradients are concerned, has been the first criteria of risks prevention zoning.

In order to get the information about the subsidences in detail, for each of the thirty craters was made the calculation of:

- The maximum subsidence speed per day.
- The average subsidence speed per day.

Comparing the two graphics (Figure 5), it can be observed that for the case of the maximum speed the difference among the data corresponding to each crater is much higher with respect to the average speed case, which is more stable.

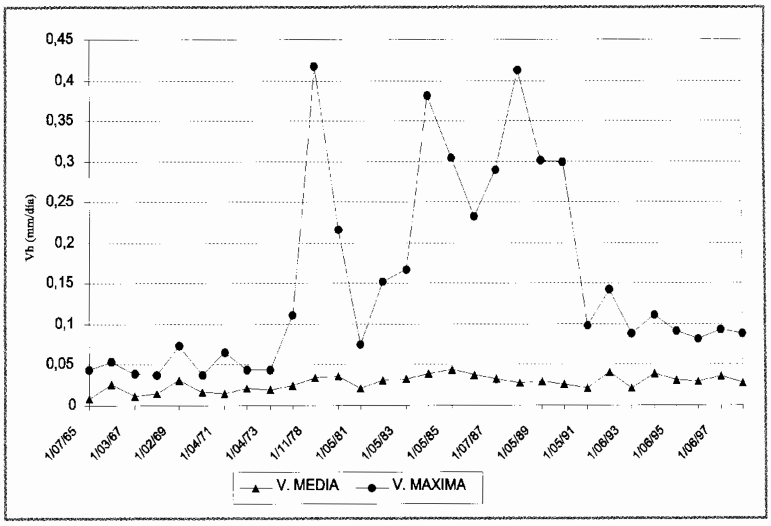

Figure 5. Subsidence velocities.

The average speed behaviour is much more regular due to the relatively small influence of a high subsidence on the average subsidence suffered in the area nearby.

The next step in order to delimit the areas according to their level of risk, was to generate the crater of subsidences accumulated within the period 1986-1998 (Figure 6). Therefore, it would be possible to obtain the subsequent plane of accumulated-gradient isodata for such period, 13 years, considered of a great importance for the zoning objective.

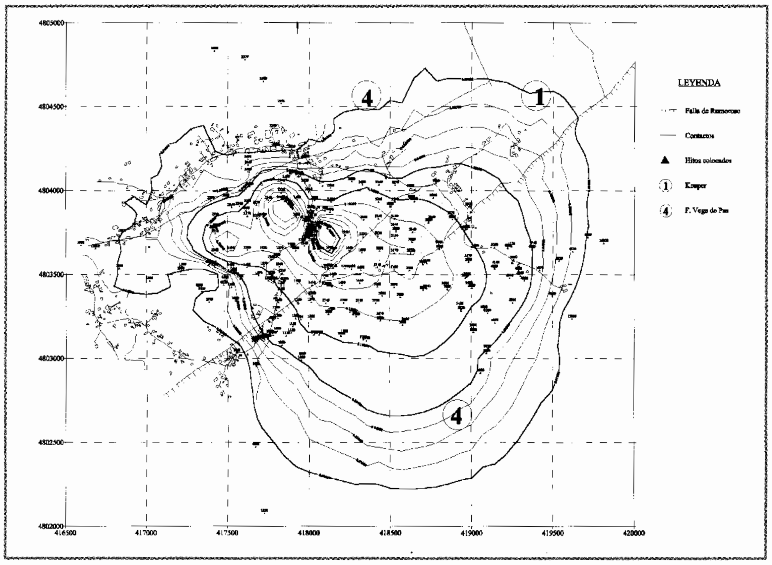

Figure 6. Subsidence accumulate during the period July/86 till Jully/98.

The methodology followed was to draw between two close isosubsidence lines their perpendicular (maximum gradient line), and calculate afterwards the data of this parameter (gradient) as the quotient between the difference of the isosubsidence lines considered and the length of the perpendicular between them.

The calculation of the data obtained allowed to delimit four different areas (Figure 7) for Bjerrum's criteria application (1963), which relate the gradient data (angular distortion δ/l) to the security limits of its effects on surface. The data that delimit such areas are:

- 1/1000 < δ/l < 1/750
- 1/750 < δ/l < 1/600
- 1/600 < δ/l < 1/500
- 1/500 < δ/l

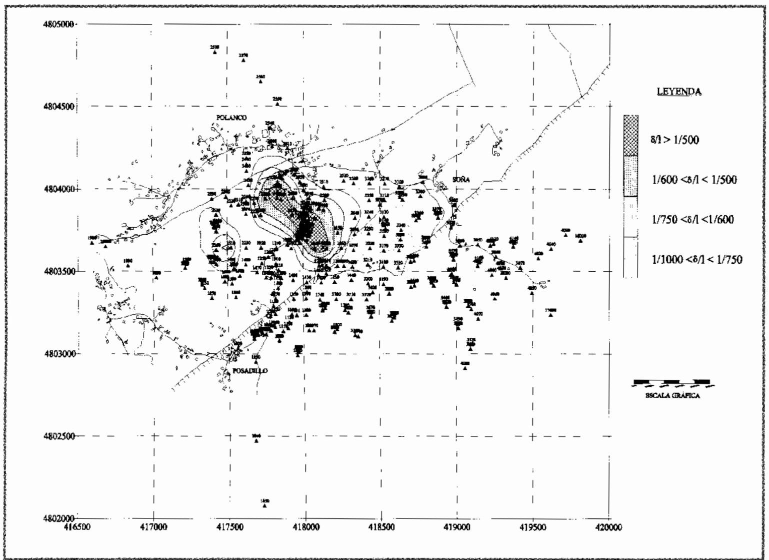

Figure 7. Accumulated dips (86/98).

It is obvious that the gradient data calculated for other different periods of time would imply a different zoning.

DELIMITING THE RISK CRITERIA

The criteria for risks zoning have been delimited according to:

- The analysis of the 30 partial subsidence craters, with respect to the maximum subsidence zones for each one of them.
- Establish a security perimeter around the craters, covering the S-451 roadway's most affected section due to the subsidences.
- The gradients data obtained within the period 1986-1998 and Bjerrum's criteria application.

DELIMITING THE AREAS OF RISK (Figure 8)

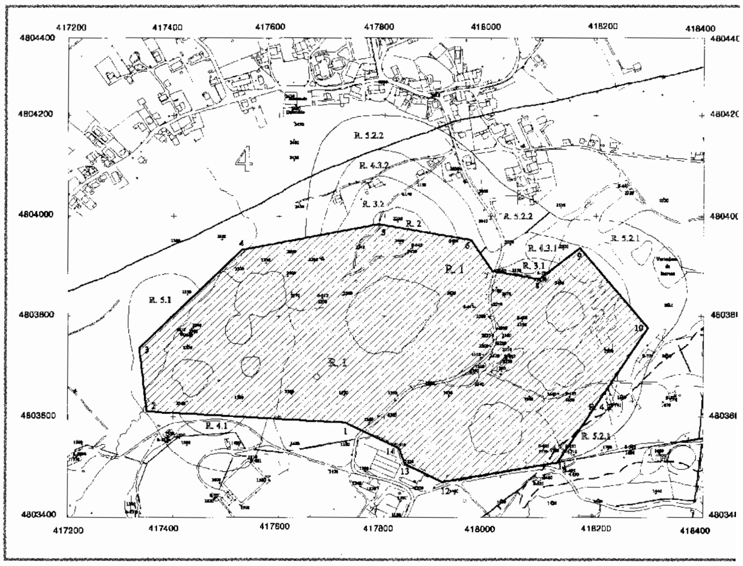
Figure 8. Risk areas.

Delimiting through the two first criteria application

By means of the research and analysis of the 30 subsidence craters generated for the period 1965-1998, it has been possible to delimit geographically the zones with the greatest subsidences for each levelling campaign. These zones are located systematically near all the craters full of water and on both sides of S-451 roadway.

The security perimeter has been set up near the craters full of water at a distance ranging between 70 and 170 m from the middle, according to: the crater dimensions and the location, orientation and type of geomorphological leaps nearby (rifts, sinkholes). As far as the zoning effects are concerned, the area located within the perimeter is named Site 1 (S1).

Delimiting through the application of the obtained gradients criteria (86-98)

The application of Bjerrum criteria, which relate the gradient data to the security limits of its effects on surface structures, has allowed to delimit four different sites, named S2, S3, S4 and S5. In turn, some of them have been divided in subsites.

LEVELS OF RISK. LAND USES

Throughout the analysis and application of:

- All the information obtained from the research
- The geographic location of sites and subsites
- The Subsidiary Norms of Polanco's City Council Planning the sites have been classified according to the following levels and typology:

Site	Level of risk	Kind of risk
1	1	High
2	1	High
3	2	Moderate tending to high
4	3	Low – Moderate
5	4	Low – Very low

The land uses are shown in the following chart:

and of those which could be produced due to the future exploitation development.

- However, in Keuper domains, where it is considered not to carry out any new exploitation, subsidence effects will still occur insofar as it happens nowadays. Their origins are located in the exploitation undertaken in boreholes drilled before 1958. The future exploitation site is planned to be in Vega de Pas' Formation domains, S-SE of Polanco. Therefore, the subsidence will be obviously increased, but the magnitude of its effects is estimated not to correspond to those observed at present in Keuper domains.
- Risks zoning can not and should not be considered as "static", on the contrary it has a totally "dynamic" character because of its boundaries. Therefore, its lands uses are conditioned in time and space to any change on the subsidence data and to the period deemed for the accumulated gradients calculation.
- In the Report of Research the risks sites are delimited and its lands uses qualified. This report must be considered as a "starting point and alive document" that has to be taken in consideration in order to adopt the measures and decisions linked to the urban development projects and land uses at Polanco.

Site/Subsite	Land Uses
S1	The uses mentioned in Art. 107 and 113 of the Applicable Subsidiary Norms shall not be permitted
S2	The uses mentioned in Art. 107 and 114 of the Applicable Subsidiary Norms shall not be permitted
S3.1 and S3.2	The same considered for sites S1 and S2 is applicable
S4.1	Limited to what it is mentioned in point 2 Art. 107, except for the boreholes drilling (*) Alternative to the new S-541 section project
S4.2/S4.3.1 and S4.4.3.2 Eastern area	Completely and exclusively restricted to maintenance, infrastructure or environmental restoration proceedings linked to the exploitation
S4.3.2 the rest	Exclusively restricted to the buildings mentioned in Art. 107.1.a Edification Projects submitted to technical considerations
R5.1 and R5.2.1	What mentioned for S4.2TS4.3.1 and S4.3.2 eastern area
R5.2.2	Art. 88 for S.U.1 and Art. 107.1 for N.U.3

CONCLUSIONS

The main conclusions derived from the development of these works are as follows:

- The final results correspond to the information analysis for the period 1964-1998.
- It is quite hazardous to make a specific technical pronouncement about the possible incidence on surface as a consequence of the present subsidence processes
- Taking the subsidence data for the control landmarks and carrying out their analysis, along with the controls maintenance in the phases of boreholes exploitation and after-exploitation are the basic tools that must allow to know the evolution, in time and space, of the subsidence phenomena and their effects on surface, and to adopt the security measures required.

BIBLIOGRAPHY

ITGE, 1976. Spanish Geology Map. Scale 1:50 000, No. 34, Torrelavega.

ITGE, 1996. Geological Survey of the diapir edges at Polanco.

ITGE – CIMA from Cantabria, 1998. Research about geological risks derived from the brine exploitation at Polanco (Cantabria).

Johnson, K.J., 1995. Land Subsidence Above Man-Made Salt-Dissolution Cavities. Symposium on Land Subsidence, in Sacramento, California. J.W. Borchers Ed. (U.S. Geological Survey). Star Publishing Company.

SOLVAY QUÍMICA, S.L. Documentation supplied.