Contribution of the GIS and the Geostatistical to the Numerical Modeling of the Polymetallic Bodies in the Tighza Mining District (Central Morocco)

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Abstract: In recent years, the Geographic Information Systems (GIS) have expanded rapidly and cover many fields including that of geological cartography and mining geology, which GIS is commonly used in both phases of mining exploration and exploitation. The usefulness of this new approach is summarised in the spatial information and updating information on the geological context, geochemical distribution, geophysical anomalies distribution and metal concentrations in order to develop mining production by directing the mining exploration and exploitation work. In the Tighza Mining Center, the various departments of the Touissit Mining Company registered (TMC), especially, the department of geology, provide a considerable quantity of information and database, which the volume is growing. On one hand, the organization and storage of this information in order to avoid possible loss, on the other hand, their treatment and their rational exploitation were behind the creation of a digital model of polymetallic body in the district. This modeling was undertaken by using the enormous potential of GIS in terms of collecting, analyzing, processing and dissemination of information for to assist the mining managers to take appropriate decisions. In this work, the ArcGIS software was used to develop a spatial database by scanning, georeferencing and development of a number of information layers from different maps: (1) Topographic maps (district boundaries, contours, spot heights, drainage pattern, roads, tracks, localities, wall). (2) Geological maps (geological, overlapping, faults, mineralized veins and metamorphic aureole). (3) Geochemical data (geochemical profiles: 4178 geochemical samples were digitized, which 2105 analyzed samples). (4) Cores drilling data (329 cores drilling, which 377 analyzed samples). Subsequently, we proceeded to the alphanumeric data integration, consisting of a description of each graphic object contained on each information layer. A Digital Terrain Model (DTM) of Tighza sector was developed by basing on digitized contours and spot heights from the topographic map 1 / 5000. The digitized contour interval is at 5 m and the altitude is between 1060 and 1490 m. This Digital Terrain Model (DTM) will allow us the automatic generation of profiles, the development of slope and exposure map and the generation of flow nets. This work is complemented by a statistical and geostatistical treatment. So, a multivariate analysis, by using principal component analysis (PCA) has identified the principal factorial axes. The geostatistical treatment of geochemical data has firstly consisted to a variograms modelling of different chemical elements. Then, it has consisted to the production of variographic maps. Finally, it has been to an establishment of the spatial distribution maps by kriging for each element. The obtained thematic maps could lead to the development of a geochemical model, which is informing about the distribution of metals in this district.

Keywords: GIS %Cartography %Mining geology %Statistics %Geostatistics %Tighza %Central Morocco

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INTRODUCTION

In the current context of globalization where the boundaries often become virtual, the governments and companies requirement to manipulate phenomenal quantity of data associated to a particular geographical position, makes GIS an important discipline which terminology continues to grow. The geological cartography and mining geology are fields where GIS are widely used in both phases of mining exploration and exploitation.

In the Tighza Mining Center, the Touissit Mining Company registered (TMC) is facing a problem of information organization and storage which generated by its various departments, especially that of geology at its 3 exploitation sites (Signal, Ighrem Aousser et Sidi Ahmed). Faced with this situation and taking into account the volume of product data, which continues to grow on one hand and their possible loss on the other hand, the, the Touissit Mining Company decided to establish a geographic information system by means of a computerized database which allows the storage, processing, interpretation and access to information on the geological context, geochemical distribution, geophysical anomalies distribution and metal concentrations, in order to guide the exploration and exploitation work and to assist the mining managers to make suitable decisions.

This work is complemented by a statistical (multivariate analysis) and geostatistical treatment of the geochemical data and the realization of thematic maps which can lead to the development of a geochemical model providing information on the polymetallic mineralization distribution in this district.

Monograph of the Tighza Mining District

**Geographic Location:** The Tighza mining district is located in the north east of Central Morocco, near the western edge of the Middle-Atlas Causse, about thirty kilometres in the northwest of the Khenifra city and 7 km from the M'rirt city. It is accessible via the main road N 24 joining Azrou to Khénifra, thus via the Secondary Highway 209 which connects M'rirt to Meknes (Fig. 1a).

**Geological Context:** Geologically, the Tighza mining district, part of the Kasbat-Tadla-Azrou anticlinorium, rightly illustrates the Hercynian geology of the greater unity of the Moroccan western Meseta. It consists of the Paleozoic sedimentary rocks of Ordovician to Carboniferous (Fig. 1b). These lands are affected by a low regional metamorphism (anchi to epizonal) which have been distorted by the different phases of the Hercynian orogeny which structured the entire region of Central Morocco into an ensemble of the anticlinoria and synclinoria and the transcurrent shearing zones with a repeated games allowed the establishment of a

![Fig. 1: Geographic location (a) & geological context of Tighza mining district (b)](image-url)
polymetallic mineralization economically important of economic importance [1-8]. The vein mineralization, which hosted in the Paleozoic formations, are represented by the Pb, Zn, Ag, W and Au. They are currently being exploited by the Touissit Mining Company (TMC). It provides 52% of the Pb national production, 26% Ag and 3.2% Zn. The annual production is 350 000 t/t, 30 000 t Pb and 4 000 t Zn. The reserves are estimated at over 5 millions t/t [9].

**Lithostratigraphic Study:** The Tighza mining district Land range from the upper Ordovician to upper Visean included. These series are approximately complete depending on location. The Ordovician and Upper Visean land profusely outcrops in this district while the Silurian outcrops are very limited (Fig. 1b).

**Ordovician:** The Ordovician land are the massifs of Aouam, Anajdam and Iguer oujana represented by the allochthonous material from the M'ريفt groundwater. The attributed deposits to the upper Ordovician allochthonous or autochton are essentially detrital, showing basically a serie of the dark micaschist alternating with the sandstone and mudstone. The quartzites bars associated to the microconglomerates are installed at the top [10].

The M'ريفt Ordovician is dominated by the clay or clay-sandstone with rhythmic character. Its top part shows the characterizing facies of the Upper Ordovician sandstone-pelite micro-conglomerate, which overlain by quartzitic bars.

**Silurian:** The Silurian suggests a lithological succession represented by the deposit mainly wisp detrital. It directly installed on the uppermost quartzite of the Upper Ordovician allochthonous. It is represented by the bluish-gray sandstones-mudstones platelets surmounted by the graptolite argillaceous mudstones and the black to red purple mudstones. These facies are respectively known in the J. Aouam district as the Mokattam shale and compartmentalized shale.

**Devonian:** The lower Devonian deposits consist of the clay indicating a quiet sedimentation of the external platform, which is rich in nodules and limestone. This carbonate sedimentation will undergo a disturbance, since Upper Devonian. It continues with the silty clays deposits containing the wisp limestone intercalations supporting many syn-sedimentary indices which indicate the substratum instability [6].

**Carboniferous:** The Touraisian sandstone-conglomerate and greywacke series are unconformably deposited on the previous land. Then they are topped by the marine deposits of platform consisting mainly of means Visean bioclastic limestone, calcareous sandstone and marl. A thick detrital serie (flysch) of the upper Visean develops by this platform deposits and completes the regional sedimentary cycle.

**Tectonic Study:** The structuring of Paleozoic formations of all central Morocco to the anticlinal and synclinal units oriented NE-SW is produced by the major phase of the Hercynian orogeny called namuro-westphalian phase.

The Tighza mining district is located in a slip and groundwater zone inside the center of the Azrou-Khenifra Visean basin [3]. The various structural studies have helped highlight the polyphase character of the Hercynian orogeny and distinguish the three major episodes of deformation [8].

A phase of post-Devonian intense folding, this first folding phase corresponds to a intense deformation represented by the soft folding of Paleozoic series. The tectonic phases prior to Visean are generally the most often very difficult to judge because the later phases, which are superimposed, tend to obscure their effects.

A phase of post-Visean folding, it is the most important phase, which is responsible for the current architecture and the cutting of district to monoclinal units.

A brittle phase (pre-Visean) composed by the several episodes. It resulted by the succession of compressional and extensional tectonic regimes, to the creation of an EW shear zone and a dense network of fractures NE-SW and EW deeply rooted, through which the hydrothermal circulations could be channeled and thus control the development of polymetallic mineralization.

**Magmatism and Metamorphism**

**Magmatism:** The establishment of the very varied magmatic bodies in the central Morocco is linked to the variscan tectonic. In the Tighza mining district, the post-orogenic acid magmatism is represented by:

Microgranodiorites and microgranites veins cartographically aligned along the NE-SW direction and
rarely EW. At the outcrop, they exhibit a color difference from light gray to light pink. This difference is related to the minerals nature which compose it [6].

Granitic stocks which the number is four, they are aligned along a NS axis, from the north to south, the granitic stocks are represented by: (1) the Tighza peaks, (2) arsenopyrite granite, (3) granite of the mine, (4) kaolin granite. The Tighza pitons were not shown because they are very small. These granite outcrops developed in the rocks an aureole of contact metamorphism which is at the origin of a significant polymetallic mineralization.

Metamorphism: In the Tighza district, there are the metamorphic rocks from the regional and contact metamorphism [8].

Regional Metamorphism: It is developed during a relatively short time period which corresponds to post-Visean structuring, it is accompanied by a paragenesis (chlorite-illite) which characterizes a epizonal metamorphism [6].

Contact and Hydrothermal Metamorphism: This metamorphism develops in the sedimentary series from the Upper Ordovician to Upper Visean, it affects three facies types: limestone, shale and sandstone.

The magmatic and hydrothermal activity within the district accompanied by the development of a metamorphic aureole centered on granitic stocks, this halo occupies an area of 3 km x 2 km. In fact, the halo is formed by the superposition of two distinct phenomena [6, 8]:

A contact metamorphism, mainly thermal and topochemical.

A hydrothermal metamorphism, resulting from the hydrothermal fluids circulations.

Mineralizations: The Tighza mining sector is a polymetallic district comprising a very varied mineralization. Indeed, in addition to Pb-Zn-Ag, the district also includes the mineralizations in tungsten, molybdenum, arsenopyrite, gold, also the antimony and barite mineralizations. These polymetallic mineralizations are the result of the operation of a polyphase hydrothermal system. The concentrations of Tungsten (WO3) and Gold (Au), are the early and the mineralizations of Lead, Zinc, Silver, Antimony, are the later stage. In the Tighza mining district, the mineralization is generally presented by veins.

Tungsten Mineralization: They are located in the aureole of the contact metamorphism caused by the granitic stocks intrusion, two mineralizations groups are being developed:

Skarns mineralizations, which its formation is due to the hydrothermal solutions infiltration, providing the tungsten mineralization in calcareous and sandstone-schist rocks of Silurian-Devonian. It is due also to the dissemination at a local metasomatic transfer [8].

Vein mineralization, which its establishment has been after the skarn mineralizations in an open fractures system corresponding to an average compression direction NW-SE. The temperature and pressure conditions of the tungsten mineralization filing were determined by [1] at 580°C and 18 Kbar for the skarn, also 400 to 450°C and 1 Kbar for the veins.

Antimony and Barite Mineralization: The antimony deposits are spatially independent of the lead-zinc deposits and gold deposits, they belong to the stibnite metallogenic province in central Morocco [11]. It is always implementation vein mineralization in the microgranites fractures (Tighza) or along of the faults affecting only the Paleozoic sedimentary formations (deposits to the East of Aouam).

Gold Mineralization: In the Tighza mining district, the gold mineralization is not a recent discovery, it was already mentioned by [11]. Among the supporting structures of this mineralization, include [8]:

Vein Structure:

C W1 vein, especially the W1 north, WO3, W4 and W5,
C Structure in W1 north,
C Structure in the east of the arsenopyrite granite,
C Structure in SW of the arsenopyrite granite,
C NW-SE structure in the Signal roof (arsenopyrite vein in NW of the Signal),
C W2 structure and Tighza structure,

Pyrhotite and arsenopyrite skarns, mainly those in the arsenopyrite granite contact, but also outside of the kaolin granite,

Pyrhotite-arsenopyrite disseminations in the Visean land, this disseminations are discovered in boreholes intersecting the North structures (north veins) and in the south of the near sector of the kaolin granite.
Lead-Zinc Mineralization: This is a mineralization represented mainly by the large veins, hosted in the Siluro-Ordovician schist and quartzite, the Devonian limestones and sandy shales, locally crosscutting the granite body.

The lead-zinc mineralization occupies a fracture system comprising from North to South, a series of simple or compound veins, almost always parallel. The whole is limited by a North system including the North and parallel veins, In addition to a South system oriented ENE-WSW, composed by the Sidi Ahmed, Ighrem Aoussa and Iguer Oujjna veins. It is developing between these two systems a fractures network extending NE-SW to EW (Signal system). The veins generally have a complex structure; they are accompanied by the parallel branches approximately continuous. These branches can attach to the veins or individualized [8].

CONTRIBUTION OF GIS TO THE NUMERICAL MODELING OF MINERALIZED BODIES

Methodology: Acquisition and Processing Data: The data numerical modeling on the topography, geology and geochemistry as well as the available cores drilling data in the Tighza polymetallic district has been achieved through the establishment of a GIS database. The approach consists of transcripts of various types of available maps (planimetric representation developed in this paper), in digital format. It includes the following steps:

Scanning and Processing Image: This step allows us to scan the geographical information contained in paper (maps) to digital images (raster). The delicacy of this step is mainly attributable to the scanner resolution used (A0). The scanned image processing was done by the "Photoshop" software to improve the display image quality.

Georeferencing: The georeferencing is an important step in the achieving and managing of databases. The georeferencing process in "ArcGIS" software is to match each image pixel to a geographical coordinates pair (in meters for example). The best adjustment and distortions correction of georeferencing depends on the choice of a several control points. This process is used to display the image in a spatial context. The advantages of this step can be summarized in: (1) the juxtaposition with the other data layers occupying the same geographical space; (2) the measure on the computer the geographical coordinates, distances and actual areas.

Digitization of Available Maps and Development of Different Information Layers: The next step consists in the tracing and vectorization of all information contained on the scanned images map; namely; (1) Topographic maps (district boundaries, contours, spot heights, drainage pattern, roads, tracks, localities, wall). (2) Geological maps (geological, overlapping, faults, mineralized veins and metamorphic aureole). (3) Geochemical data (geochemical profiles: 4178 geochemical samples were digitized, which 2105 analyzed samples). (4) Cores drilling data (329 cores drilling, which only 36 analysed (377 analyzed samples)). These graphic data are then organized into layers of information (Fig. 2, 3).

Integration of Alphanumeric Data: This step has enabled the database development, consisting of a description of each graphic objet contained on each information layer. The alphanumeric data are stored as tables in the files.

In the Tighza sector, the digital terrain model (DTM) has been developed by basing on digitazd contours and spot heights from the topographic map 1 / 5000. The digitized contour interval is at 5 m and the elevation is between 1060 and 1490 m (Fig. 4). This digital terrain model (DTM) will allow us the automatic generation of profiles, the development of slope and exposure map and the generation of flow nets. The DTM developed with an excellent resolution is, without doubt, a very useful document.

Statistical Analysis of the Geochemical Profiles: The data statistical analysis is essentially to describe the relationship between the variables and observations in our data matrix. This matrix consists of p variables and N individuals. Thus, our statistical series consists of 33 quantitative variables measured in 2105 individuals sampled in different sites (Fig. 5). The quantitative variables taken into account in this treatment are the levels of heavy metals (Li, Be, B, V, Cr, Co, Ni, Cu, Zn, As, Sr, Y, Nb, Mo, Ag, Cd, Sn, Sb, Ba, W, Pb, Bi, Ge and Se) and the contents of major elements (SiO2, Al2O3, Fe2O3, CaO, MgO, K2O, MnO, TiO2 and P2O5).
Fig. 2: Geological & metallogenic maps developed by using the GIS tool

Fig. 3: Geochemical profiles & Cores drilling maps
Fig. 4: Digital Terrain Model (DTM) of the Tighza mining district

Fig. 5: Location map of the geochemical profiles

The main objective of this study is to strip these geochemical data by statistical and geostatistical approach whose the aim is to firstly give an overview on the geochemical behavior and on the other hand, recognize the dispersion of the polymetallic mineralization constituting the Tighza mining district. The profiles were made and organized so as to align in a NS direction. In total, 2105 samples have been made following 45 lines with the same variables. The samples are approximately distributed as follows a regular grid of about 10 m.

Principal Component Analysis (PCA): In a first step, we work by taking into account all of the geochemical profiles without elimination and with a uniform weighting. The study was performed by using the centred reduced data. The first analysis after calculating the distance profiles in the gravity center G of the points cloud showed the existence of individuals (a total of 41 samples representing only 1.9% of all profiles) which have a very large distance to the origin. So they contribute significantly to the total variance.
Therefore, these individuals are called atypical. On account of their strong contribution, they are removed before entering the principal component analysis (Fig. 6).

So, the data matrix to be processed is an array of 2064 individuals and 33 variables. We conducted a multivariate technique of principal component analysis (PCA). It consists of a hierarchy of contained information in a data table by calculating the maximum elongation axis of a points cloud as follows a several axes. This method allows us to highlight the interrelationships among variables and possible similarities between individuals or individuals groups which present the similar characteristics on a particular axis.

The principle of the geochemical data treatment in principal component analysis technique is to combine the chemical elements which have the similar chemical characteristics by creating for each grouping a synthetic variable: the "principal component". This technique synthesizes the inter-elementary relationships by extracting the eigenvectors of the correlation matrix. It develops the linear combinations of the original variables which produce the factors expressing the inter-elementary relationships. A set of the new uncorrelated variables, for which we have the numerical values at each sample point is generated. The models of principal component analysis are calculated by using MINITAB V.16 and XLSTAT statistical software.
Fig. 8: Projection of the variables & individuals according to the first four factorial designs absorbing the maximum total variance.
The interpretation of the principal component analysis factors is an important basis of our study, which are based on our work of the sampling mediums characterization. Thus, the geochemical campaigns samples are ordered along a factorial axis, so that those who most resemble vis-à-vis the principal component are grouped along this axis. Each principal component contains a part of the total described information by its "eigenvalue". We interpret jointly a several factorial axes, we cumulate the expressed information on each principal component.

The distribution of the total variance in terms of the factors noted a dominant first principal component explaining about 23.87% of the total variance. So, for the better data representation, we take the first principal components; with the first ten selected factorial axes (F1, F2,..., F10), we have nearly 67.38% of the inertia (or dispersion) of all point cloud (Fig. 7).

The correlation circles (Fig. 8) distinguish two poles, one negative and the other positive manifested by the anomalies of metal concentrations following (we present here only the results of the five principal axes):

- **C** The factorial axis 1 (23.87% of the variance) is positively determined by Cr, Ba, Y, K2O, V, Nb, B, TiO2, Be & Al2O3; and negatively by SiO2.
- **C** The factor axis 2 (8.34% of the variance) is positively determined by Sb, Nb & K2O; and negatively by G, MnO, Fe2O3, Mo, Bi, Li, MgO, Co, CaO & P2O5.
- **C** The factor axis 3 (6.38% of the variance) is positively determined by Cd, Sb, Fe2O3, MnO, Pb, As, Zn & Cu; and negatively by Sr, CaO, V & Mo.
- **C** The axis factor 4 (5.88% of the variance) is positively determined by Zn; and negatively by Cu, As, Sn, W, Cd, CaO, Mo & Sr.
- **C** The axis factor 5 (5% of the variance) is positively determined by Sn, MgO, Sr & CaO; and negatively by Mo, Ge, Bi & V.

The individuals who define the five principal axes are many and varied, making the graphic too busy and unreadable. We quote for example, some individuals which determine their effect on the principal axes:

- **C** The factorial axis 1 (23.87% of the variance) is positively determined by the individuals D/109, Q/133, PNS/CC2, P/121, X/126, L/119, V/107 & E/5; and negatively by the individuals AK1, AL3, AI101, PNS/DD103, AI100, AO8, A/25 & Q/21.
- **C** The factor axis 2 (8.34% of the variance) is positively determined by the individuals V/119, L/116, W/123, U/106, T/125, Q/123, S/120 & F/117; and negatively by the individuals PNS/CC111, H/11, D/8, B/0, PNS/BB17, AO17 & F/13.
- **C** The factor axis 3 (6.38% of the variance) is positively determined by the individuals P/137, G/102, AF11, N/103, AM6, J/14 & H/8; and negatively by the individuals K/134, PNS/BB26, AN11, AJ15, L/135, AN10 & AO25.
- **C** The factor axis 4 (5.88% of the variance) is positively determined by the individual I/3, X/28, AL10, B/2, R/115, O/11, C/119, W/4 & P/29; and negatively by the individuals L/136, K/109, H/121, R/138, M/136, X/108 & I/108.
- **C** The axis factor 5 (5% of the variance) is positively determined by the individuals B/110, R/24, AN19, AC7, A/119, S/4, PNS/AA14, AB18, AA7 & G/3; and negatively by the individuals PNS/BB29, F/32, C/121, AO26, PNS/EE11, PNS/CC30, E/5 & D/114.

The principal component analysis results provide the degree of the chemical elements association with the factors. These results help to determine how much of the variability of a particular chemical element is attributable to the variations of the mineralized bodies and the associated factors with a specific mineralization.

**Ascending Hierarchical Cluster (AHC):** The Ascending Hierarchical Cluster is an automatic method of the complementary classification of the principal component analysis. It can classify the individuals or individuals groups previously identified by the PCA method. The AHC technique proceeds by successive aggregation of the individuals and individuals groups in terms of their similarities in comparison to an ensemble of criteria. So, this procedure involves a choice of two criteria for the grouping of the individuals and individual classes.
Many grouping criteria are related to the objectives of our study and the variables type that we use. The first criterion is the choice of the distance between the individuals (Index which measures how two individuals are different). The second criterion concerns the distance between the individuals groups.

In this study, we performed an Ascending Hierarchical Cluster method to all 2064 individuals by using the Ward criterion (Minimizing the intra-class variances and maximization of the inter-class variances). This classification provides a set of partitions represented as a tree called dendrogram or classification tree that
allows us to establish the individuals groups based on their geochemical similarity. Ten classes are distinguished (Fig. 9):

Geostatistical Study of the Geochemical Profiles:
In this subsection, we propose to establish the geochemical profiles cartography for each chemical element by using the geostatistical modeling (kriging). It suffices to make the estimate calculating experimentally the spatial structure and modelling it. It is the aim of the variography, which is the heart of geostatistical analysis. This study was was performed by using the SURFER 8 software. It consists of three steps:
C Establishment of the experimental variogram and fitting a model,
C Production of the variographic maps
C Kriging for mapping.

The search for the anisotropies is then refined by calculating the experimental variogram in several directions and we study the direction difference. We will simply present in this article for example only six calculated variographic maps of 33 (Fig. 10). These maps are made with a pitch h between 31m and 1566m. The geostatistical studies based on the calculated variograms from the variables show the anisotropy in the mineralization distribution contained in the Tighza deposit. The anisotropy is marked at the NE-SW major axis and NW-SE minor axis.

When the model is properly adjusted, the interpolation can be performed anywhere. The Kriging is often made on a regular grid to obtain the studied variable map. The Figure 11 shows the estimated concentrations result of each chemical element by kriging. This map reveals the important concentrations trends throughout the studied district.

CONCLUSION

The inconvenient, cumbersome and slow to access to the transcribed geographic information onto paper are so many reasons which encourages the responsible mining managers to model through a GIS, the spatial available data. The graphic modeling of the bottoms and the important spatial database quantity can be accessed at almost to the geographic information for its use and update and therefore improving the efficiency and profitability of the considered process.

The computerized work, performed on geochemical profiles data of the Tighza mining district, is complemented by a statistical and geostatistical treatment of the geochemical profiles, also the establishment of the thematic maps which used to develop a geochemical model informing about the polymetallic concentrations distribution in this district. The statistical and geostatistical methods are the reliable, rapid and quantitative means for the study and interpretation of such geochemical profiles, which are many. They bring clear undeniable added value for the cartography, evolution analysis and mineral contents variation. This added value lies in:

C The use of the intrinsic spatial structure of the phenomenon to its estimate,
C The rigorous integration of auxiliary variables which associated to the interest phenomenon by thereby improving the estimation
C The quantifying the associated error with each estimate.

This statistical work will be complemented by a statistical and geostatistical treatment of the mineralized veins and those of core drilling data, in order to synthesize a comprehensive summary of the polymetallic body distribution in the Tighza mining district.

ACKNOWLEDGEMENTS

This work was performed under the Project III D15/31 Protaras and with the support of the fellowship granted by the National Center for Scientific and Technical N°b11/006. and the Touissit Mining Company registered (TMC). We thank all who contributed, in one way or another, to make this work. A particular thankx to the TCM geologists and the Directorate, which they like to express our gratitude.

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