Analysis of Underground Block Caving Mining Induced Surface Movement in Papua, Indonesia

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https://hdl.handle.net/2324/14899

出版情報：九州大学工学紀要. 69 (2), pp.49-64, 2009-06-22. 九州大学大学院工学研究院
バージョン：

Memoirs of the Faculty of Engineering, Kyushu University, Vol.69, No.2, June 2009

Analysis of Underground Block Caving Mining Induced Surface Movement in Papua, Indonesia

by

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(Received May 8, 2009)

Abstract

The occurrence of the surface movement is the main focus of the study regarding to the gold & copper underground block caving mining in Papua, Indonesia. The underground mining has brought some environmental problems on the terrain surface such as the lowering of the elevation followed by growing of the waste pile as the result from the failure of the rock slope.

In this study, the surface movements due to the underground mining were analyzed by using the aerial photogrammetry method and the Geographic Information System (GIS) technology. The detected surface subsidence ranging from 1.5 to 2 meter and the development of the sedimentation area has been identified in which the maximum deposit thickness is about 2 meter. In addition, the correlations between extraction thicknesses over the overburden versus ground movement have been studied in order to find out the influence of some geological conditions in the development of the surface changing.

The surface movement induced by underground mining causes some serious environmental impact not only above the extraction zones but also the surrounding areas. Some environmental impacts due to the surface movement are reviewed and discussed in this paper in order to describe the current situation of the underground mining in Papua, Indonesia.

Keywords: Block caving, Subsidence, Aerial photogrammetry, GIS, Environmental impacts

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1. Introduction

The Freeport Indonesia Cooper and Gold (PTFI) mine is located in Papua, the easternmost province of Indonesia, and the western half of the island of New Guinea that has been operated for over 25 years. There are two open pit mines and underground mines at elevations of 2,500 to 4,200 m above sea level. Esberg open pit mining began operation in 1973 and the Grasberg open pit mine began large-scale open pit mining in 1988 (**Fig. 1**).

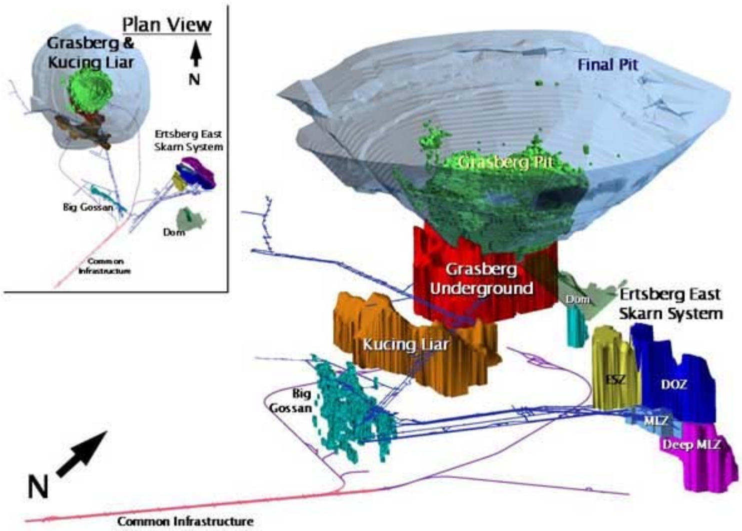

Fig. 1 3D plan view of mine area.

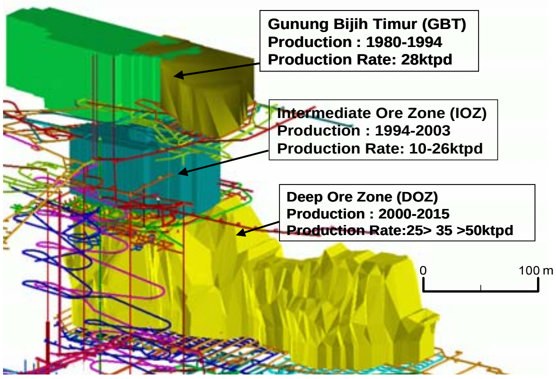

Fig. 2 3D levels of underground block caving mining and its production rate.

The underground mining complex began the block cave operations in 1980 with the Gunung Bijih Timur (GBT) block cave and was depleted in 1994. The Intermediate Ore Zone (IOZ) block cave began production in 1994 and was depleted in 2003. In 2000 an adjacent orebody named the Deep Ore Zone (DOZ) was added to the reserve base. The block caving induced subsidence may endanger mining infrastructure and is a major concern for operational safety. The subsidence crater generated by the block caving is usually creating concentric lines of the surface fractures.

Block caving is accordant to ore bodies that have weak structures (e.g., fractured or hydrothermally altered) and will collapse under their own weight with a minimum of blasting [2]. The subsidence crater generated by block caving usually forms concentric lines of surface fractures.

This crater has its major effects immediately over the mined-out block, although subsidence usually occurs outside of this area and is subjected to the angle of draw which depends on the nature and thickness of overburden [17)]. Subsidence has always been a consequence of underground mining to at least some extent, beginning when the first rock fell on top of a person working underground for the purpose of extracting a mineral resource. **Figure 2** shows the 3D levels of the underground block caving mining and its production. 3 levels of extraction area are: (1) GBT extracted from 1980-1994 and located at 3627 m above sea level, (2) IOZ extracted from 1994-2003 and located at 3457 m above sea level, and (3) DOZ extracted from 2000-2015 and located at 3126 m above sea level.

The block caving that has induced subsidence will cause danger to mine infrastructure and is a major concern for operational safety. Moreover, changes of surface landforms brought by block caving subsidence will cause quite dramatic environmental problems and safety hazards; and can also affect geologic structures overlying the mining areas which may result in surface impacts on the natural geomorphology and land use.

2. Detection Surface Elevation Change Using Aerial Photogrammetry

Remote sensing data such as Landsat ETM, SPOT, Ikonos, SAR data and aerial photography are already widely used to detect environmental hazards, such as detecting subsidence in coal mines and detecting landslide area. In the research area, almost every day is covered by cloud, satellite imagery is very difficult to used, and the most suitable is aerial photography. Multi temporal aerial photography is powerful tools that provide periodic monitoring for many different disaster applications such as detecting subsidence risk area due to block caving underground mining. In this case, aerial photogrammetry can be used in locations which are difficult or impossible to access from the ground, have complex geological conditions, steep slope and the height of 4000 m., while direct measurements in the field using geodetic method is difficult and dangerous. In this research flight planning and multi temporal aerial photography was prepared by PT Freeport Indonesia. Two types of aerial photography are applied in this research, namely the panchromatic aerial photos from 1995 to 2000, produced by McElhanney Consulting Services, and the medium format aerial photos from 2002 to 2007 produced by P.T. Exsa International Co. Ltd. The detail specification of aerial photography used in this research is shown in **Table 1** and the work flow of detecting subsidence is shown in **Fig. 3**. Although the aerial photogrammetry method has been widely used in various applications so far, in this research, the method is combine with GIS technology to detect spatio-temporal surface changes in the study area.

2.1 Ground Control Points (GCP)

The instrumental component of establishing an accurate relationship between the images in a project, the camera/sensor, and the ground is the Ground Control Points (GCP). The GCP are identifiable features located on the earth surface that have ground coordinates in X, Y, and Z. A full GCP has X, Y, and Z (elevation of the point) coordinates associated with it. The horizontal control only specifies the X and Y, while the vertical control only specifies the Z [8)].

GCP consist of any points which positions are known in an object space reference coordinate system, in this research, the reference coordinate is UTM system with WGS 84 datum. The gauging of the GCP was carried out with the Differential Method GPS, by using 3 units receiver type dual Geodetic of frequency, in which one of them was attached to the base station and the two receivers were attached to the two GCP in order to determine the coordinate. After observation time of one session was completed (2 hours), one receiver at GCP was carried over to the other GCP for the next session (Leap Frogging Method).

Table 1 Aerial photography specification.

Specification	Size
Forward overlap	60%
Side overlap.	30%
Sensor array size Y	4500 pixels
Sensor array size X	3000 pixels
Dimension Y	36 mm
Dimension X	24 mm
Pixel size	50 cm
Focal length	24.9823 mm
Altitude	1000 m
Scale	1: 5000

2.2 Aerial Triangulation

Aerial triangulation method is most frequently applied to the process of determining object in the space position (X, Y, Z) or the ground coordinates of the individual points, or known as Digital Elevation Model (DEM), based on the measurements from the photographs or measurement of tie points. Aerial triangulation is used extensively for many purposes. One of the principal applications is in extending or densification of ground control or DEM through blocks of photos for use in subsequent photogrammetric operation[13)].

Besides having an economic advantage over field surveying, aerial triangulation has other benefits (Carlisle & Heywood, 2000[5)]), such as:

- Most of the work done under laboratory conditions, thus minimizing any delays and hardships due to adverse weather conditions;
- Access to many properties within a project area is not required; and
- Field surveying in difficult areas, such as marshes, extreme slopes, hazardous rock formation, etc, can be minimized.

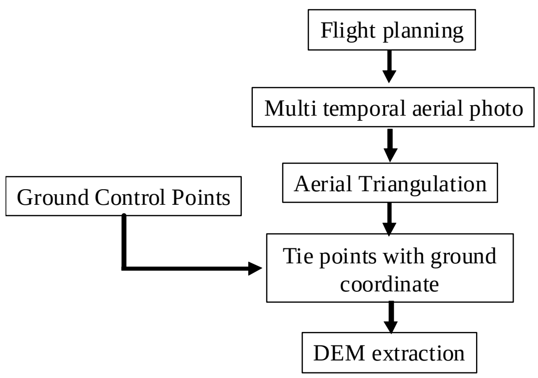

Fig. 3 Flow chart of DEM extraction using aerial photography.

Methods of performing aerial photogrammetry can be classified into three categories: analogue, semi analytical and analytical. This research uses the most modern methods, i.e. the analytical aerial triangulation. Analytical aerial triangulation methods consist of monitor-coordinates measurement of tie-point in block of photographs, followed by computation to compute coordinates of tie-points in object space and also computation of exterior parameter of each photograph. There are two steps of Analytical Aerial Triangulation[13]:

- Bridging or orientation between photos using tie points observation, by observing the tie points at least 6 points and using the coordinates of the first photo as a reference in column and row system. Then by using bundle adjustment method, the coordinate of the whole tie points and exterior parameter of the whole photographs can be computed.
- Bundle adjustment computation. A bundle block adjustment is best defined by examining the individual words in the term. A bundled solution is computed including the exterior orientation parameters of each image in a block and the X, Y, and Z coordinates of tie points and adjusted GCPs. A block of images contained in a project is simultaneously processed in one solution. A statistical technique known as least squares adjustment is used to estimate the bundled solution for the entire block while also the same time minimizing and distributing any possible errors.

2.3 Digital Elevation Model (DEM)

DEM consists of a network of sampled object values in the X, Y plane with Z values at every node of the network. A DEM may include rules of interpolation of Z values at arbitrary X, Y locations. The network data structure can be a raster, a quad tree, a triangular irregular network (TIN), or any combination of the three. DEM allows the geometrical description of the entire surface of an object by three-dimensional coordinates. DEM data can be obtained by several methods; photogrammetry is among the most common procedures. This model is a very important tool for subsidence studies. The combination of a DEM with digital image-processing techniques provides a better interpretation of subsidence phenomena at inaccessible regions or areas under risk [12].

GIS has been used for developing DEM, by computing X, Y, and Z ground coordinates of match points in the study area. In this research, more than 10.000 match points were collected. Moreover GIS tool is used to overlying DEM which is derived from successive epochs of aerial photography (**Fig. 4**). The surface topographic changing is analyzed by using GIS in order to predict characteristic of ground movement area above GBT, IOZ and DOZ block caving mining.

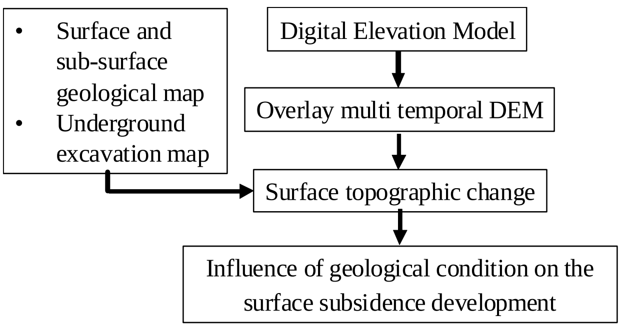

Fig. 4 Flow chart of GIS analysis.

2.4 Surface Elevation Change

Digital photogrammetry was used for DEM generation and has good precision and accuracy for detecting ground movement area based on the elevation changes, by extracting the DEMs from aerial photo which was recorded from 1995 until 2007. The ground movement area that consists of negative elevation changes was considered as subsidence area while the positive elevation was considered as waste pile area. The other possibility is the subsidence areas which are covered by waste pile area, total of waste pile height is more than deep of subsidence. The maximum negative elevation change value was -1.5 meters and the maximum positive elevation change was + 2.2 meters (**Fig. 5** and **Fig. 6**). The subsidence zone is the result of existence of the underground mining, below the subsidence area. The waste pile zone appeared as the results of the accumulation of rock fall in the steep escarpment which was accumulated in the lower part of the escarpment; and the rock fall was triggered due to steep slope and highly fractured rock.

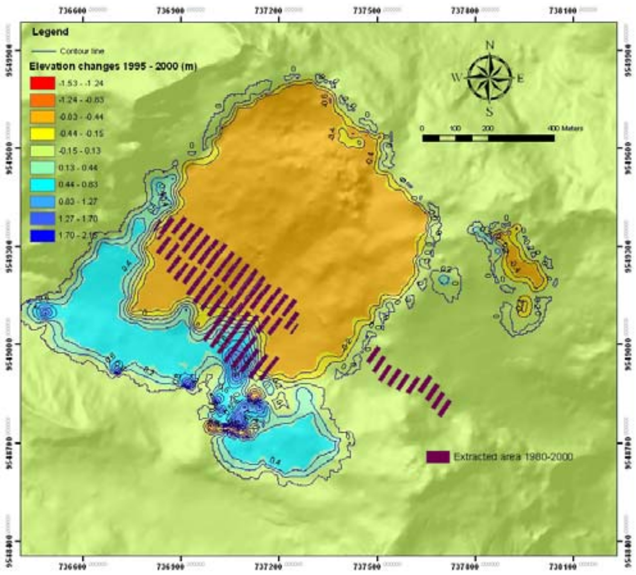

Fig. 5 Elevation change from DEMs and underground extraction area 1995-2000.

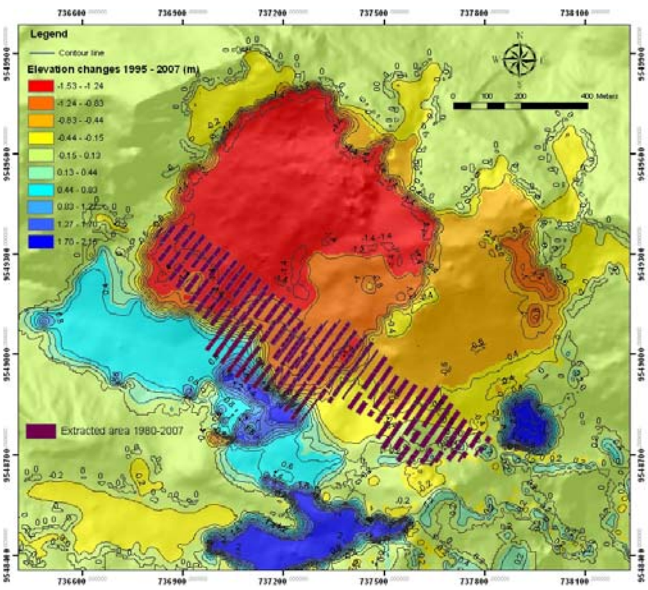

Fig. 6 Elevation change from DEMs and underground extraction area 1995-2007.

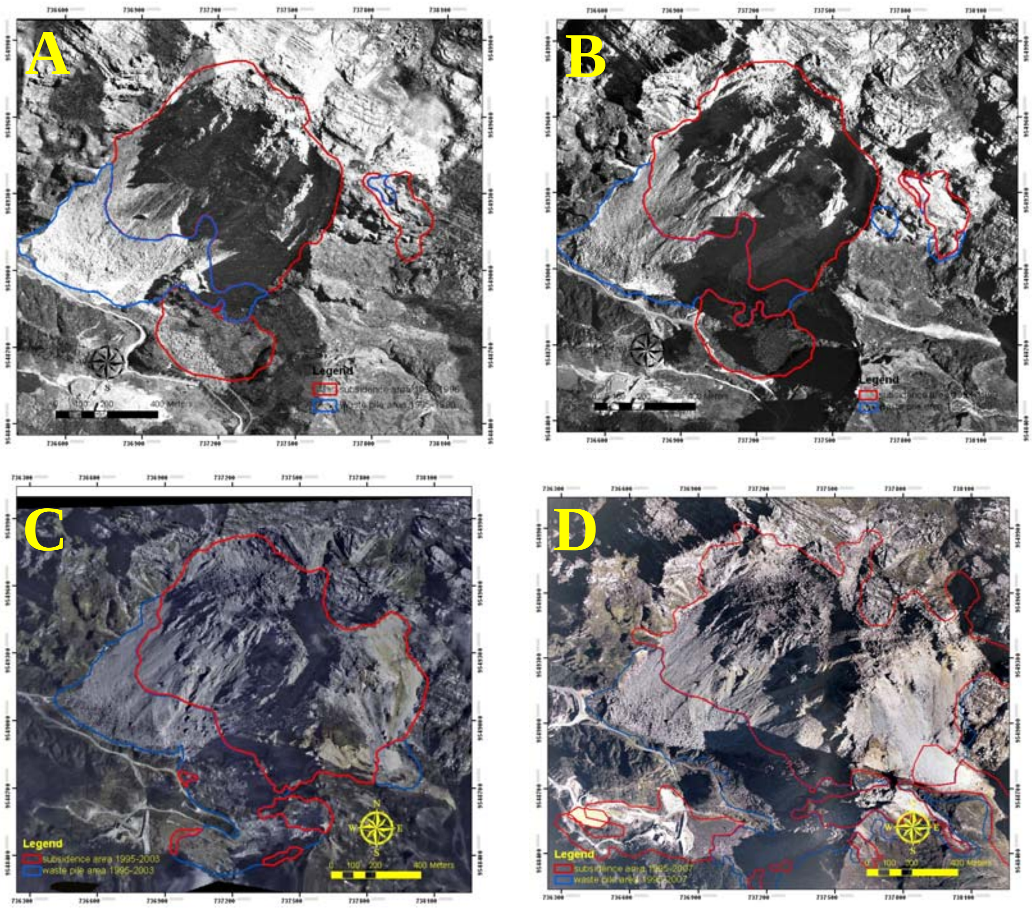

Fig. 7a Subsidence and waste pile area detected from multi temporal aerial photogrammetry. The red line is subsidence area and blue line is waste pile area. A is subsidence and waste pile from 1995 to 1996, B from 1995 to 1999, C from 1995 to 2003 and D from 1995 to 2007.

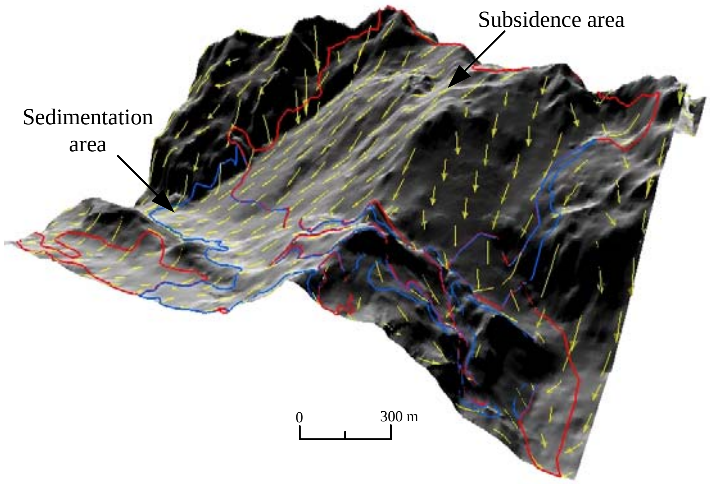

Fig.7b 3D view of subsidence and waste pile area detected from 1995 to 2007. The red line is subsidence zone blue line is waste pile zone and yellow arrow shows the direction of elevation magnitude.

3. Geological Setting in the Vicinity of Mine

The stratigraphy of the surface mine area consists of the following 5 layers: (1) Paleocene to Eocene Waripi Formation (PEW) that consists of sandy dolomite, which is composed of fossiliferous dolostone, quartz sandstone and minor limestone. (2) Eocene Faumai Formation (Ef) is composed of thick-bedded (up to 15 m) to massive foraminifera-rich limestone, marly limestone, dolostone and quartz-rich sandstone. (3) Early Oligocene Sirga Formation (Os) is composed of a foraminifera-bearing, coarse to medium-grained quartz sandstone and siltstone. (4) Oligocene to Middle Miocene Kais Formation (Mok) is interbedded marl, carbonaceous siltstone and coal. And (5) Igneous rocks in the district which are widespread as small (meters to tens of meter wide) dikes, plugs and sills into the Mesozoic and Cenozoic sedimentary rocks. The main structural features in this area are the west-northwest (WNW) trending, steeply dipping Ertsberg 1 Fault, Ertsberg 2 Fault, Ertsberg 3 Fault and the Ertsberg 4 Fault to the south. These faults have kilometer-scale and reverse-sense offsets. Geological surface such as; lithology distribution and the geological structure have been analyzed using GIS (**Fig. 8**).

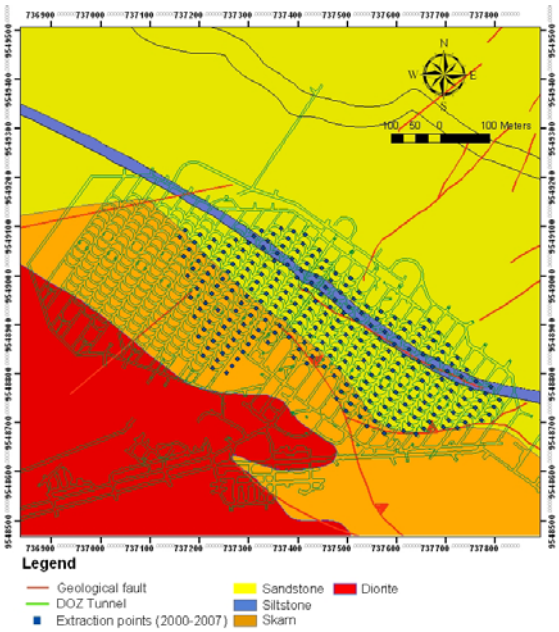

Fig. 8 Surface geological map, lithology distribution and the geological structure.

The sedimentary rocks, in the subsurface that hosted the DOZ deposit, has been hydrothermally altered into various calc-silicate mineral assemblages including forsterite, garnet, diopside, quartz, clino-pyroxene and epidote. In addition, a variety of other minerals including magnetite, anhydrite, gypsum, calcite, bornite, chalcopyrite, covellite, pyrite and hematite occurred in the deposit. The orebody is roughly zoned to the following alteration pattern, again traversing from the Ertsberg Diorite to the north: (1) Forsterite skarn, which commonly occurs adjacent to diorite intrusions, is the most prevalent rock type in the DOZ; (2) The magnetite-forsterite skarn occured adjacent to the massive magnetite zone; (3) The DOZ breccia rock type, which is found only in the DOZ, occured as a pipe-like zone that has a diameter of more than 100 meters; (4) The massive magnetite rock type commonly occured along the hangingwall zone, in contact with marble; (5) The marble rock type is comprised of re-crystallized carbonate rock of the lower to middle Waripi Formation; (6) To the west and south-west (with respect to the DOZ mine), the

Ertsberg Diorite is strongly altered along the contact with the East Ertsberg Skarn System (EESS). The sub-surface geological, lithology distribution and the geological structure have been analyzed using GIS (**Fig. 9**).

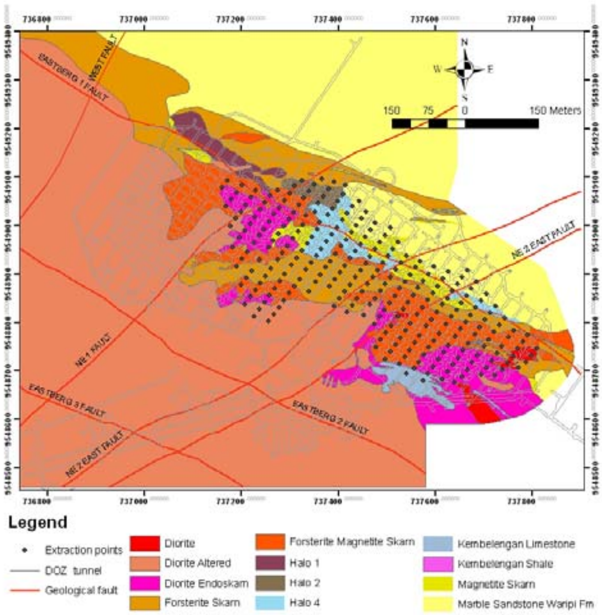

Fig. 9 Sub-surface geological map, lithology distribution and the geological structure.

4. DOZ Underground Mining

DOZ block cave is the largest single underground block cave mine in the world and the third vertical lift in the East Ertsberg Skarn System (EESS) deposit. The DOZ was discovered in the mid-1980s by deep drilling from the GBT. Portions of the DOZ were mine using open stoping methods from 1989 to 1992. In 1993, the first of several studies was completed indicating that portions of the DOZ could be successfully and economically mined using block caving methods. The production level of the DOZ block cave is at 3126 level lies at a depth of about 1200 meters below the surface. Maximum high of the extraction from 2000- 2008 is 459 meters and the minimum is 4 meters. **Figure 10** shows the extraction points (275 points) from 2000- 2008. Start form 2000, the extraction was progressed to the east to reduce impact of the DOZ caving on the operations of the IOZ block cave mine. After the IOZ was exhausted in 2004, caving was started towards the west.

4.1 Analysis of the Relationship Between Height of Draw (HoD), Overburden and Surface Subsidence at DOZ Underground Mining

The HoD is the total amount of material taken during the process of extraction while the overburden is the term used in mining to describe material that lies above the area of economic or scientific interest, *e.g.*, the rock, soil and ecosystem that lies above the extracted area (**Fig. 11**). Overburden is distinct from tailings, the material that remains after economically valuable components have been extracted from the generally finely milled ore. Overburden is removed during surface or underground mining, but is not typically contaminated with toxic components and may be used to restore a mining site to a semblance of its appearance before mining began.

Relationship between HoD/overburden and surface subsidence is shown in **Fig**. **12** and **Fig. 13.** Points in this **Fig. 12** represent the position of extraction point data at DOZ underground mining in which extracted using GIS with subsidence value and HOD/Overburden value.

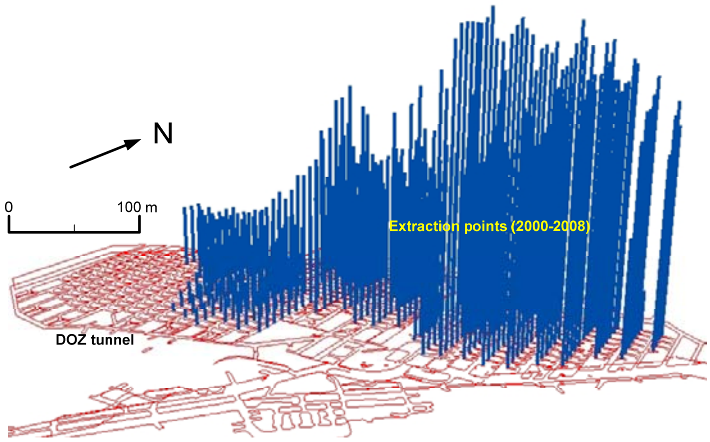

Fig. 10 3D view of extraction point from 2000- 2008.

This relationship can be divided into four areas; high waste pile area (2m ~ >0.5m), low waste pile ~ no surface change (0,5m ~ 0m), low subsidence (<0m ~ -0,5m) and high subsidence area (<-0,5m). High waste pile area located in the lower part of the surface change area, at the elevation 3900m - 3950 m, with slope at 30^{o}~ <40^{o}, and HoD/overburden value is 0,1. Low waste pile ~ no surface change area located in the middle-eastern part of the surface change area, at the elevation of 4000m - 4200 m, with slope at 10^{o}~ <40^{o}, and HoD/overburden value is 0,1 ~ 0,4. Low subsidence area located in the medium to upper part of the surface change area, at the elevation 3900m - 4200 m, with slope at 10^{o}~<50^{o}, and HoD/overburden value is 0,1~ 0,4. High subsidence area located in the medium to upper part of the surface change area, at the elevation 3900m - 4200 m, with slope at 10^{o}~ <50^{o}, and HoD/overburden value is 0,1~ 0,3.

Low waste pile – no surface change area includes the area in which subsidence and sedimentation do not exist. From aerial photos, this area shows the fresh rock and according to the geological map, this area limited by fault (**Fig. 13**). This phenomenon can be thought as the result of the existence of fault by the development of the subsidence area deceleration. Another reason is because DOZ approximately 600 meter below the surface, so that the effect is too small in the surface area. The strength of the rocks also plays a role here as well as the factor of lithology, jointing pattern and extent of the development, faults and their distribution, and the degree of weathering. Most of subsidence areas consist of sediment rocks, but the other area that have no surface elevation change, consist of skarn that have different rock strength. Besides faults, the difference of the rocks strength also has role in causing the subsidence border to decelerate. In normal condition, if there are no faults and all the lithology distribution are homogenous, the subsidence border will be in a regular shape, but in the research area, the surface is controlled by some faults and consists of different types of rock with different strength.

In the low subsidence area, there are some extraction points that have high HOD/overburden value. On normal condition, HOD/Overburden value is also low in this area. This phenomenon occurred by the surface changes in this area consist of subsidence and waste pile. Due to covered by waste pile, the area with high HOD/Overburden value has low subsidence. Another factor is the existences of geological fault and different lithological type made the development of the subsidence area deceleration.

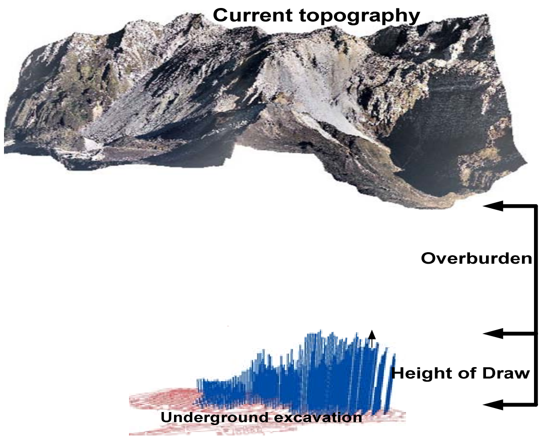

Fig. 11 Illustration of overburden and HoD.

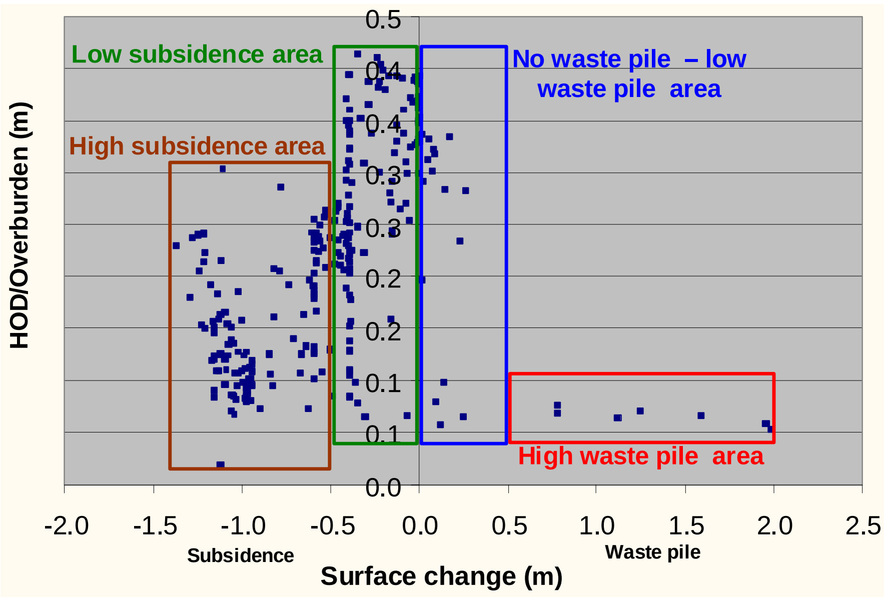

Fig. 12 Relationship between HoD/overburden and surface subsidence.

The high HoD and overburden values are shown in the south-east side of the extracted area (**Fig. 14** and **Fig.15**). The maximum overburden value is 1140 and minimum value is 750, while HoD maximum value is 450 and minimum value is 25. Extraction area with high Hod value also has high overburden value, and the extraction area having low value of HoD, surely also have low value of overburden. This phenomenon was done to keep the subsidence value not too high in the surface. However, the relationship between HoD/overburden values with the subsidence is different, such as at the area having high HoD/overburden value, not having high subsidence value. High subsidence values are shown in the area with low to middle HoD/overburden value (0.1-0.3, **Fig. 12**). This occurrence is caused by several factors: (1) this area has complex geological condition. The type of lithologies that exists in the subsidence area are skarn, sandstone and diorite and there are two types of faults, i.e. normal and reverse faults (2) the extraction areas have irregular shapes (showed in **Fig. 10**) (3) subsidence developed on mountain area which has steep ground surface slope, ranging between 10^{o} to 70^{o} (4) time dependent deformation of rock. This factor has a significant impact on the stability of rock slopes and underground structures such as underground block caving mining and tunnels. After an excavation and a support installation, the ground may continue to deform as time progresses, and may cause severe damage.

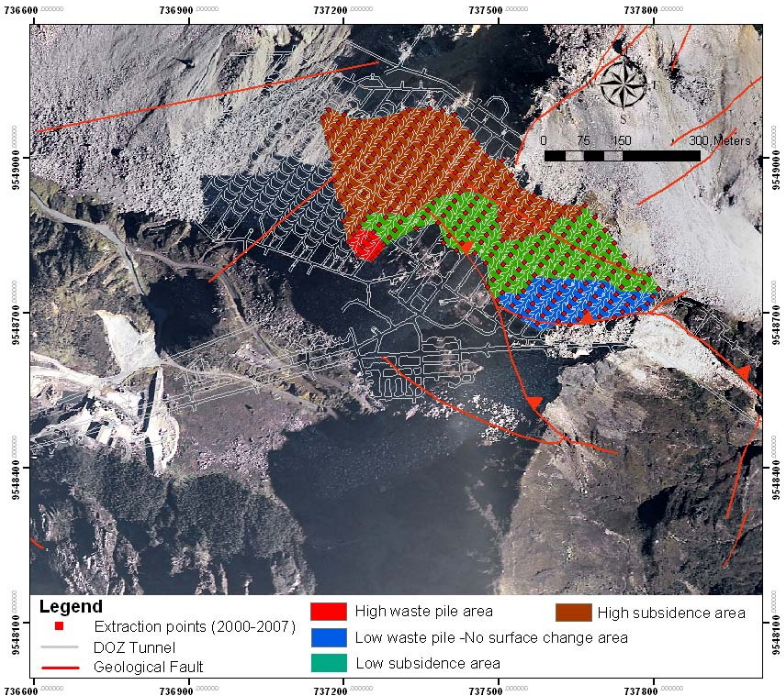

Fig. 13 Low – high sedimentation and low-high subsidence area base on relationship between HoD/overburden and surface subsidence.

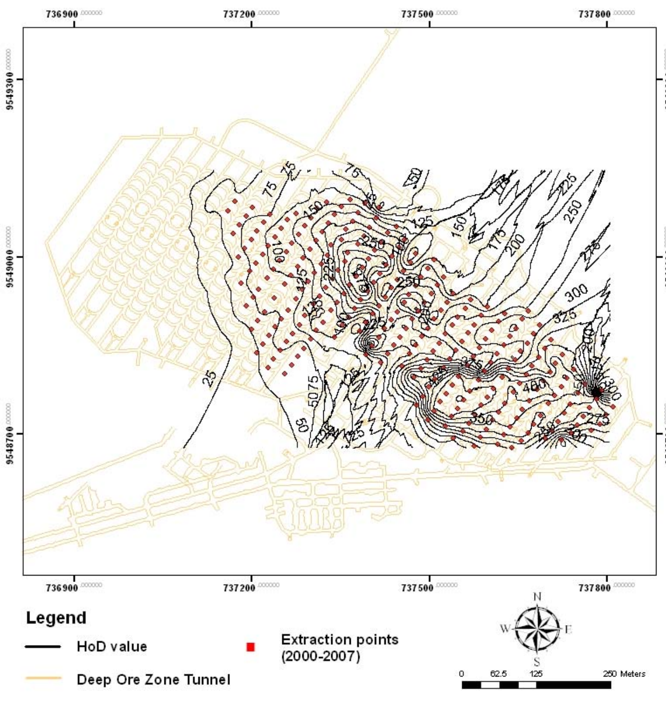

Fig. 14 Extraction point from 2000- 2008 overlay with HoD value.

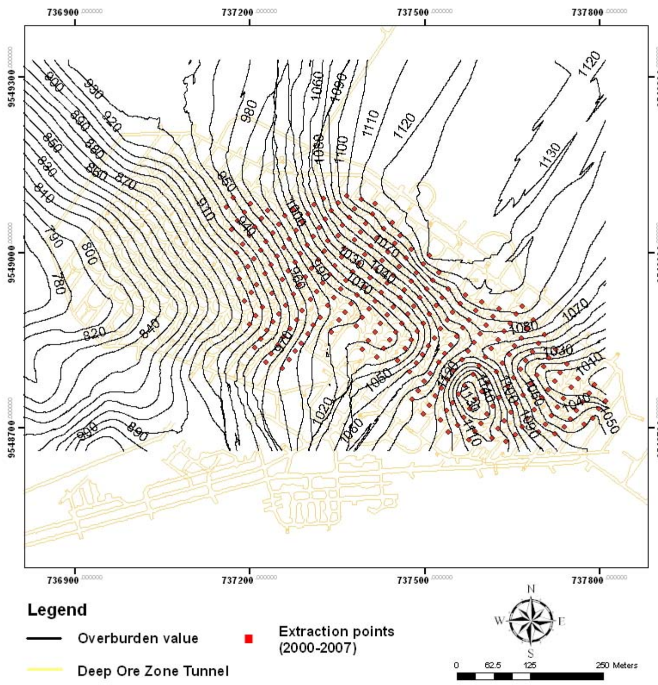

Fig. 15 Extraction point from 2000- 2008 overlay with overburden value.

5. Environmental Impact due to Underground Block Caving

Underground excavation is predicted to impact the surface and connected to the already caved areas due to the mining of the GBT, IOZ and DOZ block caves. Some facilities that are located in the potential surface change area are shown in **Fig. 16** and photos of field inspection at the surface change area are shown in **Fig. 17.**

Some facilities that are expected to be lost due to the surface change such as:

1. Existing DOM Road. This road provides the access to the DOM area. On daily operation, this access is used by the maintenance and ventilation groups, who conduct a routine maintenance to the Tuan Fans and DOZ Fans, and by the geotechnical group, who monitors the subsidence/caving propagation at the surface. Considering the importance of this road function, an alternative road has been built. The new road shown in the **Fig. 16** was made for anticipating the impact from the DOZ crack. This plan will be modified to accommodate the ESZ crack's effect.
2. DOM Office. This office and the DOM yard have been abandoned for years and are used for storing scrapped materials. There is no risk of losing these. Most of the materials have been moved following the occurrence in 2002. However, a thorough cleaning up program to this area should be completed before affected by the DOZ cave.
3. Tuan Fans. Currently, the salvaging process to the fans is in progress. By the time the DOZ subsidence intercepts this area, there will be no fans left.
4. Power Lines. These lines transfers the power required for running the DOZ fans. Moving the existing power lines to the new DOM road and adding another power line must be done.
5. Water Pond. The water source of this pond is coming from the rain. Pumping and drying up the pond is included in the modified alternate DOM road plan.

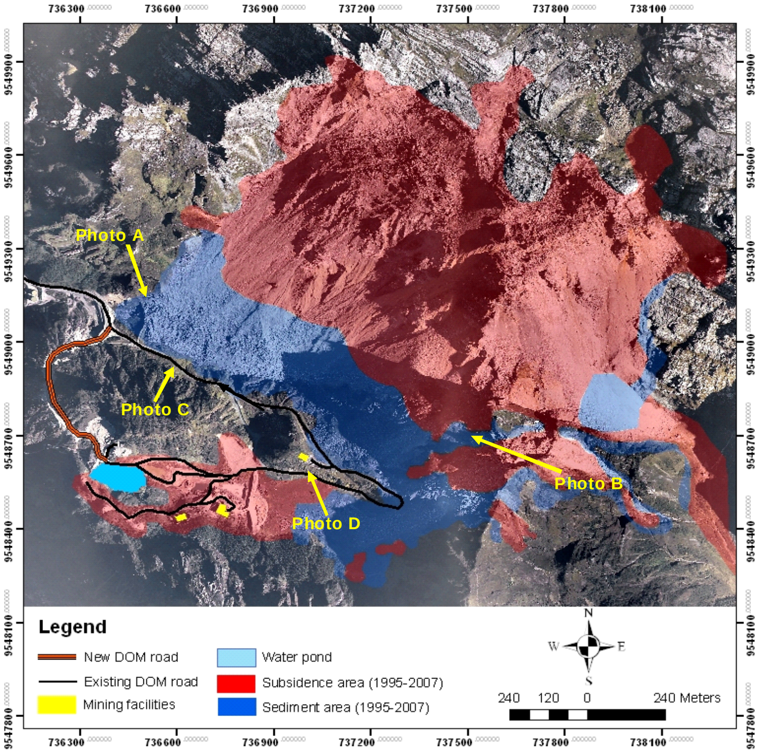

Fig. 16 Some facilities that are expected to be lost due to the surface deformation.

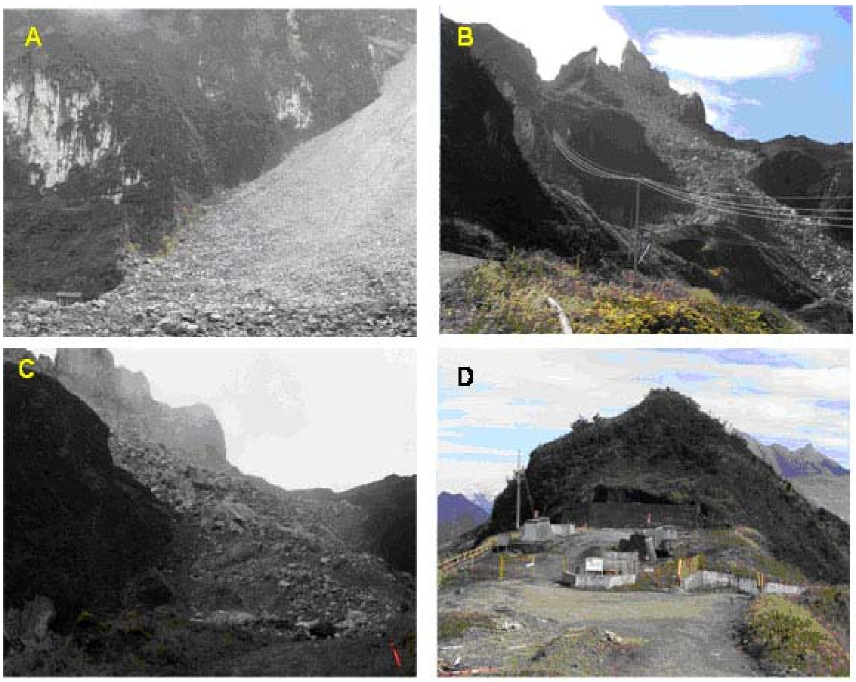

Fig. 17 Photos of field inspection at the surface change area; **A**: this point of view observed at the west side of subsidence area, the wall as the limit of cave line at the subsidence; **B**: east side of surface deformation, disturb electricity line; **C**: south side of surface deformation, close the DOM road; **D**: south-east side of surface deformation, the mine ventilation from DOZ.

6. Conclusion

Subsidence and waste pile area were detected spatio-temporally using GIS and multi temporal aerial photogrammetry analysis. The subsidence developed on the steep ground surface slope that caused slope failure phenomena on the up slope side and rock falling down into the lower area around the waste pile area.

The maximum overburden value at DOZ is 1140 and minimum value is 750, while HoD maximum value is 450 and minimum value is 25. According to this relationship between HoD/overburden and surface subsidence, can be divided into four areas; high waste pile area (2m ~ >0.5m), low waste pile ~ no surface change (0,5m ~ 0m), low subsidence (<0m ~ -0,5m) and high subsidence area (<-0,5m).

Low waste pile – no surface change area is including the area that there is no subsidence and sedimentation. This phenomenon can be explained as the result of the existence of fault, the strength of the lithology and the degree of weathering. In the low subsidence area, there are some extraction points that have high HOD/overburden values. This phenomenon was caused by the surface change in this area that consists of subsidence and waste pile. Due to waste pile deposition, the area with high HOD/Overburden value has low subsidence. Extraction area with high Hod value, have high overburden value. This phenomenon was done to keep the subsidence value not too high in the surface. High subsidence value located at area that HoD/overburden value is low to middle. This occurrence is caused by several factors: (1) this area has complex geological condition (2) the extraction areas has irregular shapes (3) subsidence developed on mountain area and has steeply slope ground surface (4) time dependent deformation of rock.

Block caving mining activities in the PT. Freeport Gold & Copper mining, Papua, Indonesia caused annually ground surface change. The type of geological condition above the extracted area has influence to the general characteristic and magnitude of the subsidence distributions. Surface subsidence and waste pile due to underground extraction is gradual process and result in the gradual development of damage. Some facilities that are expected to be lost due to the surface movement, such as existing DOM road, DOM office, Tuan fans, power lines, and water pond.

References

1) Blodgett, S.; Subsidence Impacts at the Molycorp Molybdenum Mine Questa, New Mexico (2002).
2) Blodgett, Steve & James R. K.; Underground Hard-Rock Mining: Subsidence and Hydrologic Environmental Impacts, Technical Report (2002).
3) Blodgett, S. &. Kuipers, J. R.; Underground Hard-Rock Mining: Subsidence and Hydrologic Environmental Impacts, Center for Science in Public Participation (2002).
4) Brady, B.H.G. & Brown, E.T.; Rock Mechanics for Underground Mining, 3nd edition, Kluwer Academic Publishers, London (2004).
5) Carlisle & Heywood; Effective Application of Automated Digital Photogrammetry for Geomorphological Research, Earth Surf. Process. *Landforms*, vol. 24, no. 1, pp. 51–63 (2000).
6) David, C. N.; Geologic Controls of Subdivision Damage near Denver, Colorado, Journal of Geotechnical and Geoenvironmental (2005).
7) Gilbride, L. J., Free, K. S., & Kehrman, R.; Modeling Block Cave Subsidence at the Molycorp, Inc., Questa Mine-A Case Study, The 40th U.S. Symposium on Rock Mechanics (2005).
8) Hill, K. C., Kendrick, R. D., Crowhurst, P. V. & Gow, P. A.; Copper–gold mineralisation in

New Guinea: tectonics, lineaments, thermochronology and structure, Australian Journal of Earth Sciences, 49, 737–752 (2002).

9) Jarosz, A.and Zahiri, H.; Integration of Insar and GIS for Monitoring of Subsidence Induced by Block Caving Mining. The 15th Australian remote Sensing and Photogrammetry Conference (2007).

10) King, H.J., Whittaker, B.N., & Shadbolt, C.H.; Effect of Mining Subsidence in Surface Structure, Mining and the Environmental, IMM London (1974).

11) Kratzsch, H.; Mining Subsidence Engineering, Spriger Verlag, Berlin (1983).

12) Kraus, K.; Photogrammetry, Vol.1., 4th edition, Verlag H. Stam GmbH, Köln, ISBN 3-427-78684-6 (2000).

13) Li, Z. Zhu, and Gold, Q.; Digital Terrain Modeling: Principles and Methodology, CRC Press, London (2005).

14) McNally, G. H.; Geology and Mining Practice in Relation to Shallow Subsidence in the Northern Coalfield, New South Wales, Australian, Journal of Earth Sciences 47, pp. 21–34 (2000).

15) Mealey, G. A.; Grasberg Mining, The Richest and Most Remote Deposit of Copper and Gold Mining, in The Mountains of Irian Jaya, Indonesia, Freeport-McMoran Copper & Gold Inc.1615 Poydrass Street, New Orleans, LA 70112 (1996).

16) Shadbolt, C.H.; Subsidence Engineering, University of Nottingham, Mining Department (1972).

17) Whittaker, B. N., & Reddish, D.J.; Subsidence, Occurrence, Prediction and Control, Elsevier Science Publisher B.V., Netherlands (1989).