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Collapses of old mines in Korea

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ABSTRACT

Ground collapses over abandoned mines constitute a significant geohazard in Korea. Recent collapses at the Mookeuk, Chungyang and Toehyun mines provide examples of the failures of rock over old stopes, and of old backfill that had been placed in abandoned stopes. Micro-seismic monitoring by borehole geophones is used to locate rockfalls within the Keumgok mine in order to design appropriate remedial filling. The government's Mine Reclamation Corporation has an ongoing programme of documentation and remediation of the old mines.

1. Mines in Korea

After centuries dominated by an agricultural economy, Korea (or South Korea as it is often known in the outside world) saw a rapid development of numerous metal mines in the first half of the 20th century, when the nation began to develop a major industrial base. The complexes of old igneous and metamorphic rocks were found to be rich in metal resources, and minerals accounted for over 75% of total exports in 1953. Though only about 80 mines are currently active, there are well over 2000 mines that have been abandoned since ceasing operation within the last 50 years; both these figures exclude surface quarries and some underground mines for non-metallic resources.

The geology of the Korean peninsula (Fig. 1) is dominated by metamorphosed and strongly folded Precambrian and Lower Palaeozoic rocks with numerous large and small, late Palaeozoic, granitic intrusions. In the southeast, a younger cover of Mesozoic sedimentary and volcanic rocks is less deformed, and is intruded by late Cretaceous granites. Mines old and new are scattered throughout the country, though there are fewer within the Mesozoic cover away from their mineralising granites, and there is none in the shield volcano basalts that form the whole of Cheju Island (100 km south of the peninsula depicted in Fig. 1). The small area of Carboniferous coal measures in the northeast has been heavily mined in the past, but less than ten collieries still operate.

The various geohazards from old mines, notably ground subsidence, acid mine drainage and soil contamination, are therefore significant across the whole of Korea, though individual sites are mostly isolated and of limited extent outside the small area of concentrated coal mining. The government of Korea has therefore invested heavily in mine reclamation, with many active programmes that are now also finding useful applications outside Korea itself. Four mines, all within the central upland region, and all with recent and ongoing problems of collapse and ground subsidence, demonstrate the variety of geohazards created by these old mines.

2. Mookeuk gold mine

Gold was discovered in 1891 by panning sediments a kilometre south of the small town of Kumwang, in the province of Chungchongbuk (Fig. 1). The mine was developed in the early 1900s, and gold production was at a peak through the 1930s. Mineral was extracted from a zone of steeply dipping veins, in strong biotite granite, and yielded 23 g/t of gold over vein widths of 1–4 m. After ceasing operations in 1972, the mine was re-opened in 1984 to extract both gold and silver, with workings to depths of 380 m, but finally closed in December 1997 when reserves were depleted. By then, a farmhouse stood above the oldest part of the mine at the site of the subsequent collapse, but the site was developed in 1984 to create the Somang Hospice (meaning House of Hope) for patients afflicted with tuberculosis.

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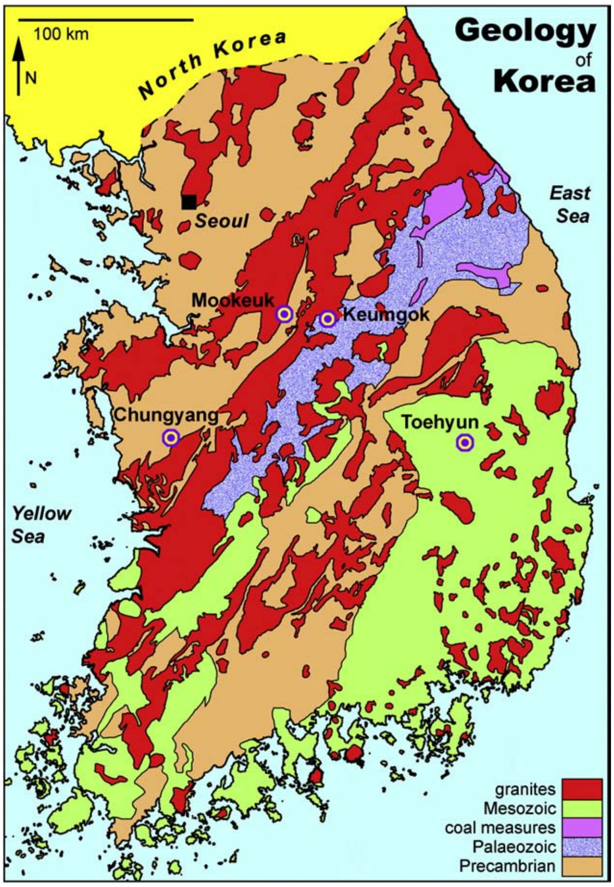

Fig. 1. Outline geological map of Korea (excluding Cheju Island) with locations of the four mine collapses referred to in the text.

The initial collapse occurred on 27 May 2008, when a hole 8 m in diameter opened in the ground to a depth of 30 m (Fig. 2). This was a sudden ground failure, only preceded by a small-scale subsidence and soil cracking for about an hour. By sheer good fortune, the collapse hole developed in the garden that was surrounded on three sides by the hospice buildings. Only some small outbuildings were destroyed, and no lives were lost.

This collapse of the ground surface occurred nine days after a short period of very heavy rainfall; 52.5 mm of rain fell on 18 May, in contrast to a mean daily precipitation of 4 mm. This was after a previous year's rainfall about 20% higher than the annual mean. The site lies in a slight natural valley that collects run-off and soil water from the adjacent slopes, though its floor has no permanent stream channel. Limited wall collapse caused the surface hole to enlarge to about 10 m across in mid-June. A larger collapse expanded the surface opening to about 15 m in diameter on 2 August 2008; this was again at an interval after another period of heavy rainfall on 19 July. Over the following 15 months, there have been no further significant changes to the collapse hole. A pile of fallen rock debris, has its top about 15 m below surface level; this slopes down for about 20 m to a remnant of rock floor visible within the mine stope that extends into darkness on the south side of the daylight hole. Collapse debris has now run into some of the deeper levels within the old mine.

A survey of the visible and accessible features was completed in August 2008, and twelve boreholes, some vertical and some inclined, were drilled to depths of 60 m to investigate the adjacent sub-surface geology. These enabled down-hole camera recording of bedrock fractures, which indicated some increased fracture opening due to rock relaxation close to the mine workings. The hospice has moved elsewhere, and the site has been left to stabilise until the surface hole can be backfilled with a reasonable expectation of no subsequent subsidence.

The ground failure at Mookeuk was over the oldest part of the mine, worked in about 1910 (Fig. 3). A stope of the Hyungje vein was worked above a roadway floor 40 m below ground level (Fig. 4). There is no surviving record of exactly how high the stope reached, but it appears to have risen to within a few metres of rockhead. A roof of granite about 5 m thick survives over the stope's continuation to the south (Fig. 2). Above this, soil and weathered rock are a few metres thick, but thicken towards the northeast (Fig. 5). There is no evidence that the rock roof had been weakened by any small shafts reaching from this stope to the surface before being capped, buried, forgotten and subsequently destroyed by the collapse. From the borehole data, RQD varies from 50 to over 90 within the uppermost 30 m of the granite, with some recognisable decline in values closer to the vein, though this is not consistent.

Fig. 2. The open collapse hole over the old Mookeuk gold mine, looking south along the line of the vein, in late 2009.

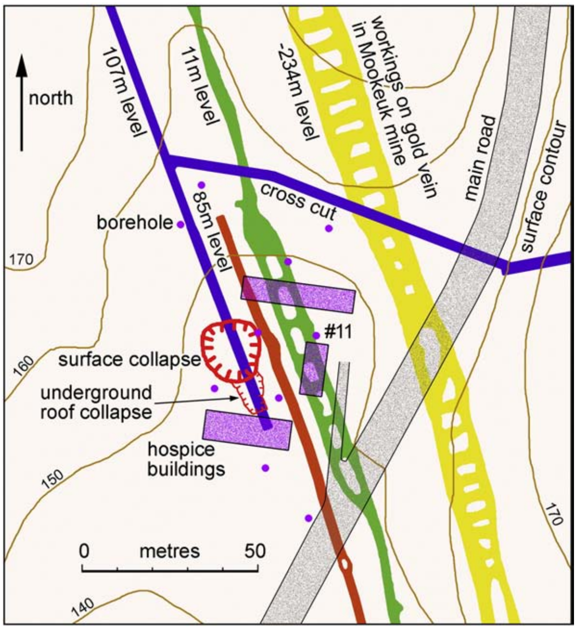

Fig. 3. Surface and underground features at the Mookeuk mine. Surface contours and mine levels are labelled in metres above sea level. Extents of the higher levels are only approximate.

The widest exposed roof span in the mine is about 6 m, but the old stope may well have expanded to nearer 10 m on intersecting or parallel veins at the site of the collapse. High fracture density, and the weak, mineralised, altered rock along the zone of veins were significant factors in permitting collapse of the old stope roof. Without these, the cover of unweathered granite left over the stope would have to have been only about a metre thick to collapse without imposed load. Clearly, high groundwater pressures following the heavy rainfalls helped determine the timing of the event, but would have had limited impact on the granite where only widely spaced fractures are now exposed in the walls of the collapse. The water table is currently about 30 m below surface level at the collapse site, with most of the mine now flooded.

It appears that the Mookeuk mine collapse was due to the final failure of undisturbed rock that spanned an excessively wide mined cavity. Without records of the stopes prior to the failure, the extent of preceding progressive roof and wall failure remains uncertain. There are small surface pits along the main and subsidiary veins, but there are no other surface collapses. In a well-populated area, and adjacent to a main road, remediation and redevelopment of the site is appropriate. It is fortunate that remedial works will not be excessively large due to the narrowness of the old workings along the vein.

3. Chungyang tungsten mine

A mineralised vein system was identified in 1912, beneath the wooded sides of a small valley 25 km southwest of the city of Gongju, in Chungchongnam province (Fig. 1). The near-vertical veins lie within, and along the axes of, thin sheets of Cretaceous quartz-porphyry that were intruded into Precambrian granite gneisses. A substantial mine operated from 1935 until 1982, producing over 16,000 tonnes of tungsten, together with bi-product gold, silver, copper and molybdenum. Stopes just a few metres wide were developed beneath the valley floor and under both hillsides, and reached a vertical range of 400 m (Fig. 6). At the north end of the mine, parallel workings were developed on a bifurcation of the main vein.

Mining extended along the vein for about a kilometre, and almost the whole of this length was developed first with narrow cuts open to the surface, where soil cover was only thin. As the mining progressed to greater depths, most of these open cuts were backfilled. As was common practice in old vein mines, much of this backfill was placed on wooden platforms across timber stemples wedged into the stope, so that mining could proceed beneath them. In the long term, rotting of the timber and consequent collapse of the backfill is almost inevitable; upward migration of the collapse commonly reaches to the surface, where it creates sudden and sporadic ground subsidence in the style of sinkholes within soil cover. Ravelling of the debris from below means that natural compression arches can develop within parts of the backfill compacted between the rock walls of the old stope, but the stability of these is normally only temporary. Depressions that now mark the line of the vein appear to be largely due to this style of backfill subsidence, though some may have been only shallow workings that therefore have a rock floor beneath minimal soil and fill.

Significant collapses of the backfill have developed recently at two sites along the Chungyang vein (Fig. 7). Each has left an open hole less than 2 m wide and about 15 m long; they both descend into darkness and their unstable walls prevent further investigation. One has exposed the outside of the concrete lining of the shaft #3, which was backfilled at some time in the past; the square shaft was set into the western wallrock on the edge of the vein, so that one side is now exposed where the stope's backfill has fallen away.

Between shafts #3 and #5, a long line of surface depressions traces the veins up onto steep slopes that are all now clad in thick woodland. These appear to be original surface workings that were probably no more than 5 or 10 m deep, and which were only ever partially backfilled. There are no signs of current or recent sinkhole development by ravelling, nor even settlement of the fill. However, there are extensive recorded stopes below the 45 m level, less than 40 m down. There is therefore a strong possibility that workings were continuous from the surface downwards, in which case open stopes

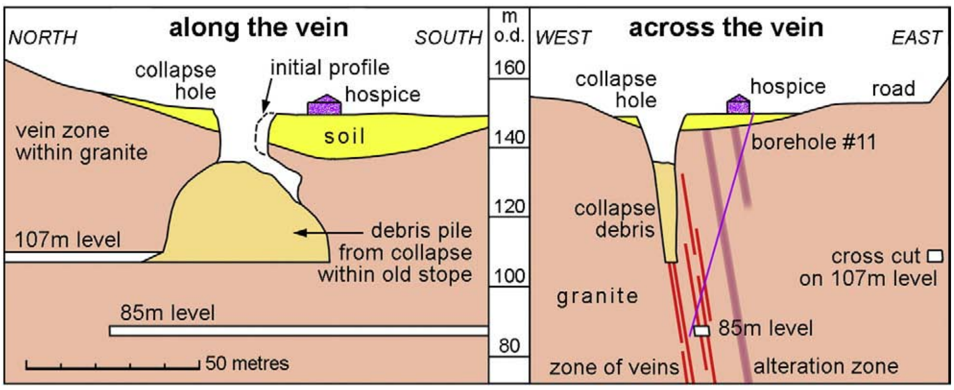

Fig. 4. Cross sections through the collapse at the Mookeuk mine, both along and across the vein.

Fig. 5. Massive granite exposed in the north face of the Mookeuk collapse.

may lie beneath timber-supported waste that floors the current surface depressions. Further investigation is required to evaluate this collapse hazard.

For about 70 m across the valley floor, the top of the vein lies beneath alluvium, and stopes within the main orebodies do pass beneath the line of the valley floor. It is likely that workings from deeper levels never approached rockhead beneath the alluvium, as the miners would have wanted to retain a solid rock barrier to prevent flooding of their mine by inflow from the river. The main river channel is now concreted where it crosses the line of the vein. The valley road shows no sign of distress. A recent borehole investigation found small mined tunnels but no large open stopes at shallow depths where the road lies over the vein. An agricultural building between the road and the river and directly over the vein is also stable.

Any geohazard from ground instability over the old Chungyang mine depends largely on the extent to which backfill is supported on timbers above open stopes and on the state of those timbers. From the appearance of the two collapses now visible, a potential threat must

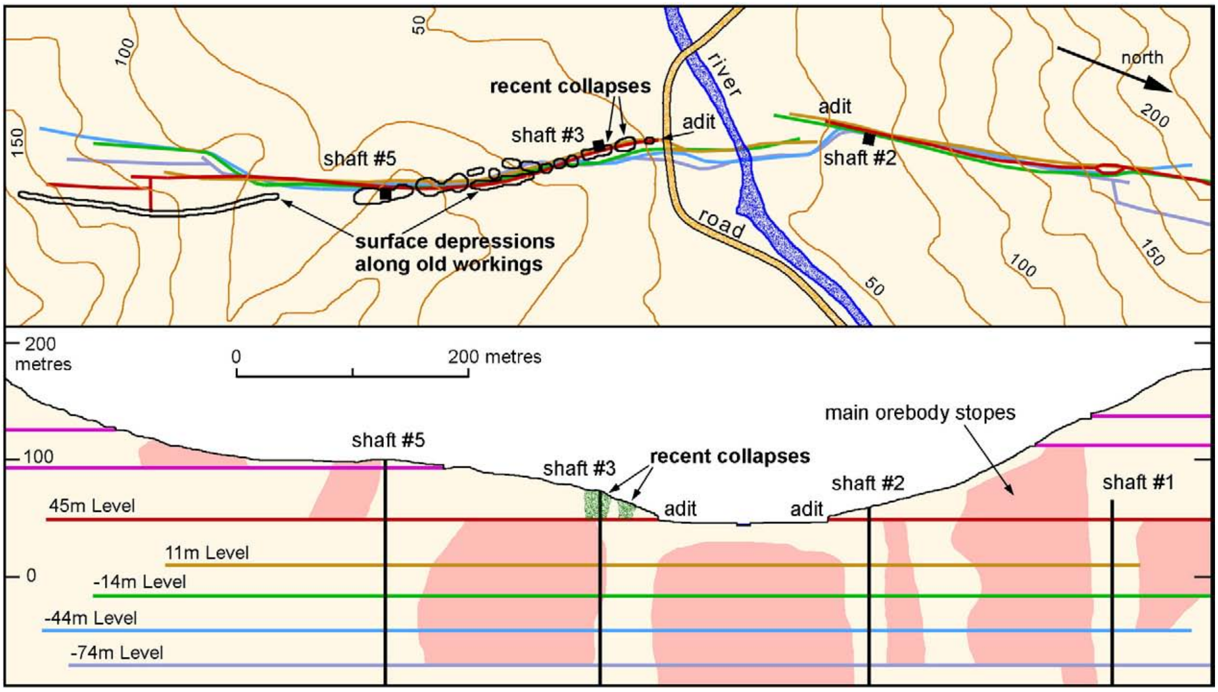

Fig. 6. Plan and profile of the central part of the Chungyang vein mine. Only the main areas of stopes within the richer orebodies are identified on the profile, and workings also reached into leaner parts of the vein; the mine extends beyond the map in both directions, and also to deeper levels.

Fig. 7. The northern of the two recent collapse of backfill over the old Chungyang mine, looking south along the main vein.

be recognised along the whole footprint of the mine. Areas with backfill that rests on bedrock pillars are likely to be stable, but the extent of these is not easily determined. The costs of remedial works may be so high that it is economical to regard the narrow strip of steeply sloping woodland directly over the mine as sterile and inappropriate for any development. The exception to avoidance of the undermined ground is the road crossing on the valley floor, but current data indicates that this is not at risk. In addition, the strong wallrocks mean that ground adjacent to the vein is not at risk.

4. Toehyun metal mine

The remains of the old Toehyun mine lie beneath a small valley just north of Sagok village, 5 km south east of the city of Uisong, in the centre of Kyongsangbuk province (Fig. 1). Its early history is unknown, but the mine produced significant amounts of gold, silver and copper from a vertical vein in steeply dipping and massively bedded Cretaceous sandstone. It closed in 1973 and was then allowed to flood. The site was restored to agricultural land with the removal of all buildings and surface structures. No detailed records of these works are known, but the valley floor was given a gently graded profile by redistribution of waste minestone that is at least 3 m to 8 m deep. Geotextiles were laid over this, and then covered by a metre of soil suitable for plant growth. This restored ground reaches 300 m down the valley, with a width of about 30 m, to a concrete retaining wall 5 m high, which now creates a step in the valley profile.

A small collapse sinkhole was first seen in the upper end of the restored ground in March 2009, during routine monitoring for soil contamination. The surface hole was only a few metres across and lay above a small inclined shaft into which the cover of restoration debris had slumped. By early April, a second sinkhole, over 10 m in diameter, had opened in the centre of the restored ground. Further wall collapse caused this hole to grow to about 20 m by 15 m in May 2009. This event appears to have been triggered by an earthquake of Magnitude 3.8, which had its epicentre near Andong, 35 km away; this would have generated ground shaking only to about Intensity IV at the mine site. Subsequent minor slumping of the restoration debris exposed in the upper walls has enlarged the sinkhole to about 18 m by 25 m, with a ramp of fallen debris down to standing water 12 m below ground level (Fig. 8).

The collapse sinkhole has revealed an opening between rock walls about 8 m apart. This appears to be an old open cut on the line of the mineralised vein. There are no signs of freshly broken rock that might indicate the collapse of a rock roof above an underground stope. It appears that the open cut was backfilled before being covered with the restoration debris, but there are no known records of the mine's development. At the southern (down-valley) end of the sinkhole a sloping rock roof descends into and below the standing water. The slope of collapsed debris can be seen running down into an underground stope over which the sandstone bedrock is intact (Fig. 9).

It would therefore appear that the primary cause of the surface collapses was the movement of backfill that had not been properly

Fig. 8. The collapse sinkhole at the old Toehyun mine, looking north, after it was enlarged during the 2009 earthquake. Broken strips of geotextile, placed beneath the soil during site reclamation, hang down the walls.

contained or engineered and therefore ran into lower parts of the mine that were still open. The geotextiles above the restoration fill were never intended to span an open void 8 m across, and therefore failed under the weight of their soil cover.

A complete restoration of the site may require judicious grouting of fill within some parts of the mine to ensure the stability of any new backfill in the sinkhole. This may involve costs that are excessive for a site is on the edge of forest land with almost no need for visitor access. The site is scheduled for a thorough investigation in the near future.

5. Keumgok magnetite mine

High-grade iron ore was produced until 1987 from the Keumgok mine, which lies beneath part of the village of Iryu, 5 km southwest of Chunju in the central province of Chungchongbuk (Fig. 1). Magnetite with minor hematite formed multiple, steeply dipping, lenticular orebodies within Palaeozoic gneisses close to the contact with a Jurassic granite. An open-pit mine, 100 m long and 40 m wide, reached a depth of 40 m in some of the southern orebodies, and

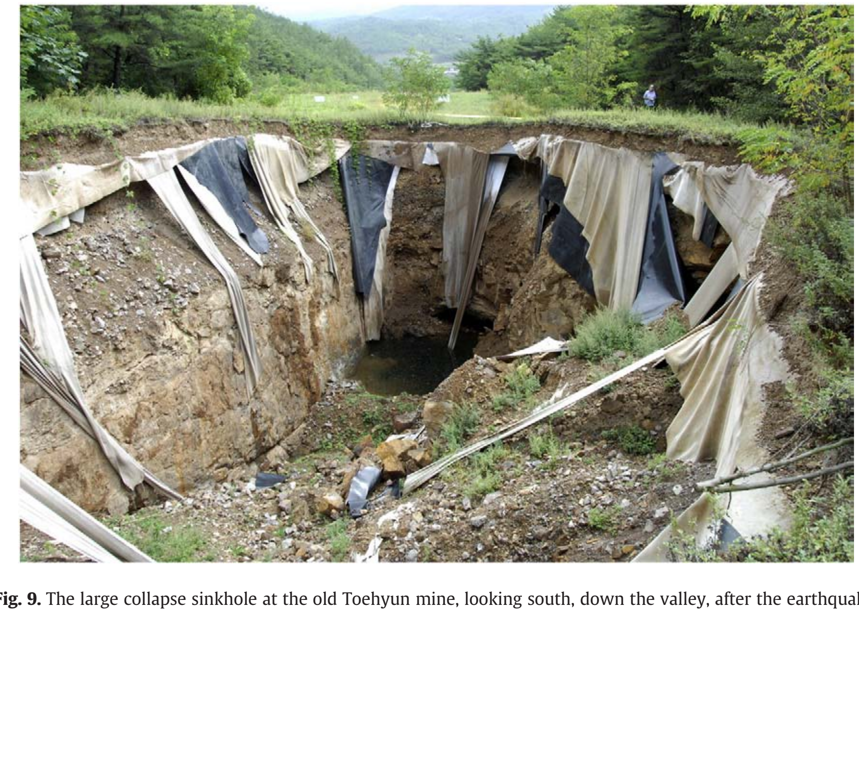

Fig. 9. The large collapse sinkhole at the old Toehyun mine, looking south, down the valley, after the earthquake.

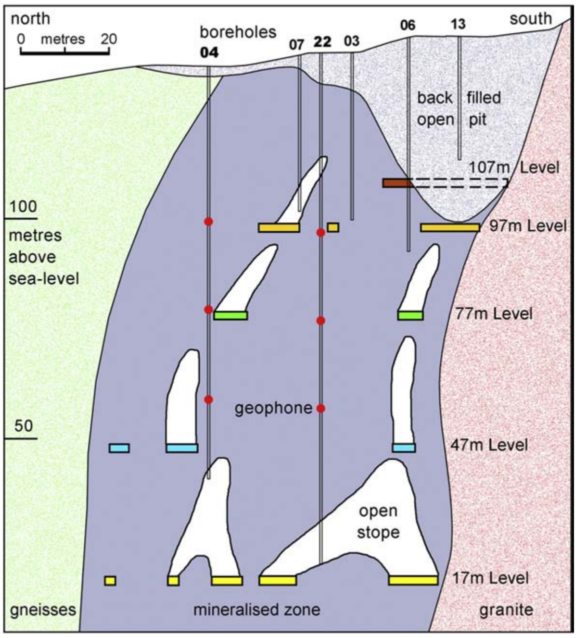

Fig. 10. Section through the old Keumgok mine, with the boreholes and geophones that are part of the current investigation. The lowest level (at −13 m) is not shown.

underground mining then continued to reach depths of 150 m along a strike length of more than 250 m (Fig. 10). The open-pit was backfilled around 1980, and the site was redeveloped in 2003 for housing. Three-storey blocks of apartments were built above some of the deeper old underground workings but avoided most of the backfilled open-pit and the mine levels with less rock cover (Fig. 11).

Residents newly housed in the apartments became concerned when they could hear, and could feel the vibrations, from sporadic rockfalls within the underground mine. It was recognised that these rockfalls could indicate progressive failures in old stopes, and some of these lie at depths of only 20–30 m in orebodies adjacent to the deeper sections of the backfilled open-pit. This prompted an investigation programme. Boreholes intersected extensive cavities in the upper parts of the old mine. They also revealed a significant zone of ground relaxation beneath and adjacent to the deeper part of the backfilled open-pit (Fig. 11). The water table lies at about 100 m, very close to the floor level in the deepest part of the old open-pit. Rock Mass Ratings were interpreted from the borehole data to lie in the range of 30 to 95, with a mean of 67 and some recognisable decline around higher levels of the old mine.

Subsequently, a programme of micro-seismic, real-time monitoring has been established to determine the locations and extent of the rockfalls, in order to design remediation appropriate for the site. A total of 30 geophones have been installed at depths of 40, 60 and 80 m in each of ten boreholes across the site (Fig. 11). These have the time resolution to be able to locate the source of any vibrations created by rockfalls within the mine. They have now been installed for nearly a year, and have not yet recorded an underground rockfall; the instruments are known to be working satisfactorily because they have recorded frequent events that originated from blasting in a quarry 900 m away.

It is apparent that the old Keumgok mine workings may eventually require filling with rock paste injected through boreholes to allow safe development of the immediate and adjacent ground. Whether the entire mine, or just the upper levels, will have to be filled can only be determined by a proper understanding of the pattern and extent of the rockfalls; the current programme of monitoring is intended to provide this.

6. Mine reclamation in Korea

Site redevelopment is much in demand in Korea where there is a significant shortage of available land away from the steep, forested mountain areas. To tackle the widespread problems associated with old mines, the government has created the Mine Reclamation Corporation (MIRECO). This group has been charged with addressing

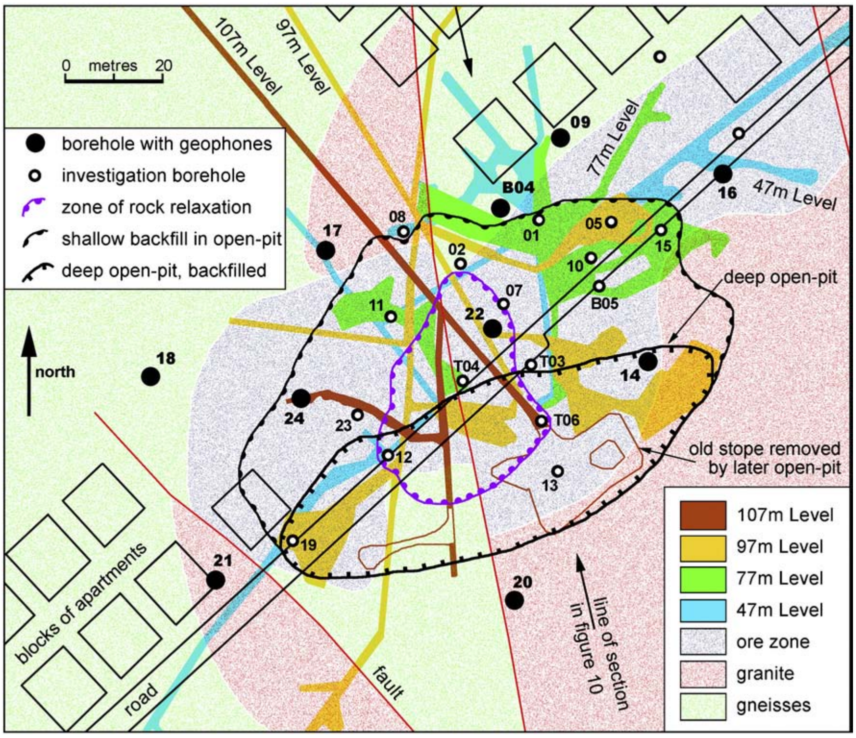

Fig. 11. Surface and underground features of the Keumgok mine. Surface level is close to 135 m across the site. Deeper levels within the mine (at 17 m and −13 m) are omitted for clarity.

the nation's mined ground with remediation of mine tailings, acid mine drainage, soil contamination and subsidence within a master plan scheduled for completion in 2026 (Kim and Kwon, 2007). Many of the difficulties for MIRECO derive from the almost non-existent records surviving from the long period of Japanese colonial rule, from 1910 to 1945, during which time the mining industry was at its peak. Most of the nation's mines have closed since then, and subsequent site reclamations are frequently hampered by little or no knowledge of the underground conditions. A major and ongoing task is therefore the investigation of the old mine sites and the accumulation of a useful data base on site-specific ground conditions.

MIRECO has also developed numerous research programmes to improve techniques of both investigation and mine site remediation. Two international symposia on mine reclamation have been held to disseminate new data and also to bring in new ideas from foreign lands with longer histories of dealing with old mines (Choi et al., 2007; Lee et al., 2009). With a major input of resources, the nationwide problems of difficult ground conditions related to past mining are being efficiently and effectively managed with the aid of GIS, and MIRECO is now taking its knowledge and techniques to other countries within the region.

Acknowledgements

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