LLNL's Partnership with Selected U.S. Mines, for CTBT Verification: A Pictorial and Some Reflexions

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1. INTRODUCTION

The verification of an upcoming Comprehensive Test Ban Treaty (CTBT) will involve seismic monitoring [1, 2] and will provide for on-site inspections [3, 4] which may include drilling [5]. Because of the fact that mining operations can send out strong seismic signals, many mining districts in the U.S. and abroad may come under special scrutiny. The seismic signals can be generated by the use of large quantities of conventional explosives [6-8], by the collapse of underground workings [9, 10], or by sudden energy release in the ground such as in rock bursts [11] and coal bumps [12]. These mining activities may be the cause of false alarms [13], but may also offer opportunities for evasive nuclear testing [9, 14].

So in preparing for future verification of a CTBT it becomes important to address the following mining-related questions:

- from a seismic point of view:
 - what are the characteristic signatures of mine shots using conventional explosives such as ANFO; what is the effect of various delays and various shot patterns on the time-histories of ground motion records; what is the azimuthal variability of the ground motion, particularly for large open-pit, cast-blasting shots.
 - what are the characteristic seismic signatures of mine collapses, such as in block caving operations, in long-wall gob subsidence, or in accidental pillar failures.
 - how well does current seismic equipment operate in a local mine environment; how accurate is the location of mine seismic events.
- from an on-site inspection point of view:
 - what is the lay-out of various open-pit and underground mines; what are common operating procedures
 - what surface expressions may result from underground collapses
 - what more can overflights reveal, when compared to surface-based inspections

For the United States, these are questions to be answered with respect to foreign mines, more particularly in countries which are not likely to be very receptive to U.S. inspections. But there is a good amount of commonality in mining methods, worldwide, regardless of location. So, studies conducted at U.S. mine sites can

provide good analogs of activities that may be carried out for overseas CTBT verification, save for the expected logistical impediments. With this in mind, Lawrence Livermore National Laboratory (LLNL) organized a partnership with several U.S. companies to carry out a field program of CTBT-related measurements. The results of those efforts in FY1995 are presented in a series of separate reports. This document is mainly a pictorial overview of the various sites.*

2. THE HENDERSON MINE, CO

The Henderson Mine, near Empire, CO, is a molybdenum-ore block caving operation of the Cyprus Climax Metals Company [15]. Block caving was seen as an analog to the collapse of chimneys overlying cavities created by nuclear explosions. A network of seismic stations was deployed by LLNL around the mine site in the summer of 1994 [16].

Figure 1 shows Red Mountain with the "glory hole" of the current Henderson operations in the foreground and that of the, now closed, Urad Mine in the center right. It also shows the rugged topography of the site with elevations ranging from 2400 m (8000 ft) in the valleys, up to 3600 m (12,000 ft) at the peaks.

Figure 2 shows the main mine shaft and surface buildings in May, 1994. Figure 3 shows the Henderson glory hole from the mine buildings. Figure 4 was taken in August 1994 from a portable LLNL seismic station installed about 10 km (6 miles) West of the mine entry. Access would be very difficult in the winter as the road is not passable; airborne access would have to be considered. Some of the stations on and around Red Mountain were in pretty rugged terrain with no road access (Figure 5).

Figure 6 illustrates the underground setting, i.e.. medium-sized tunnels in hard rock, with minimal structural reinforcement and no lining. This adit goes right to a draw point for the cave, as indicated by the rubble. Figure 7 shows a front-end loader dumping ore in an ore-pass, to the haulage level. This creates "cultural" noise from the machine operation and from the dumping process. Such noise can interfere with the operation of an in-mine seismic monitoring system.

* Photographs were taken by the author, unless otherwise noted. All the pictures, but that of Figure 1, were taken in 1994 and 1995.

3. THE SAN MANUEL MINE, AZ

The San Manuel Mine, AZ, of Magma Copper Company did function as both an open-pit mine and a block-caving operation for many years [17]. It is now moving into a new, block-caving only operation [18]. The previous block-caving has left a very large open volume underground, which is overlain by 420 m (1400 ft) of conglomerate. Figure 8 was taken in May 1994 at the surface of the conglomerate formation. It shows that the surface has subsided, without filling the underground cave. This has left very conspicuous scarps which would be noticed in an on-site inspection. The scarps are shown across both ends of the road in the middle of the picture, in the left forefront and in the left-upper quadrant. This location has been proposed for an on-site deployment to try and delineate the dimensions of the large underground void by seismic surveys. No time table has been adopted yet for such a deployment which could test how well our on-site inspection would find a very large, deeply buried cavity. The answer to the cave dimension would be of great interest to Magma Copper Co., as a sudden failure of the roof of that large cave could create a powerful and damaging underground airblast.

Figure 9, taken in September 1994, shows the now inactive open pit, and the head frames of the various shafts. Below the head frames is a zone of massively disturbed and jumbled ground due to the underlying caving operations. The area shown in Figure 8 is to the back of the head frames.

4. THE BLACK THUNDER MINE, WY

This open-pit mine, located in the Powder River Basin [19], South of Gillette, WY is the largest producer of coal in North America. In 1993, it extracted more than 30 million tons of coal. The 21-m thick coal seam (Figure 10) is overlain by about 45 m (140 ft) of sedimentary rocks. Figure 11 shows one of the four operating open pits in October 1994. The overburden is stripped away from the coal by the combined use of cast-blasting with ANFO and draglines. The amount of ANFO in a production blast can reach 7 to 8 million lbs., which is equivalent to the energy of a 3-kiloton nuclear explosion. Such mine shots could provide an opportunity for masking a clandestine, decoupled low-yield nuclear test.

On October 28, 1994 we witnessed a 3.6 million lbs. shot. A portion of the 600-hole pattern is shown in Figure 12. The result of the blast is shown in Figure 13 where the rock is broken in an area of 45 m (150 ft) transverse to the picture and 600 m (2,000 ft) in the direction of the horizon. A video of that visit and cast-shot also was made [20].

Subsequently, both LLNL and Los Alamos National Laboratory (LANL) conducted on-site seismic deployments for monitoring a variety of mining shots [6, 21].

5. THE NEWMONT GOLD QUARRY, NV

The Newmont Gold Company operates several open-pit gold mines in the Carlin trend of Nevada [22]. The largest is the Newmont Gold Quarry. Figures 14 and 15 show the mine in February 1994 at the occasion of an initial visit. The air-photo is taken from about a 5,000 m (16,500 ft) altitude. The ground photograph shows the open-pit with on-going drilling, and patterns ready for blasting. The amount of explosives is an order of magnitude less than at Black Thunder. But several patterns in the pit can be blasted at short time intervals. These may create constructive or destructive interactions at regional distances. LLNL deployed an array for seismic characterization of the blasts in the spring of 1995 [7]. Figure 16 shows the same mine in October 1995 from 3,400 m (11,500 ft) high, on a flight from California to Wyoming. From an on-site inspection point of view it is interesting to study the contrast between Figures 14 and 16.

6. THE BARRICK GOLDSTRIKE MINE, NV

Twenty miles North of the Newmont Gold Mine, the Newmont Gold Company and Barrick Goldstrike Mines Inc. exploit the Barrick Goldstrike open-pit mine [23]. It is shown in Figure 17. The size of blasts is comparable to that at the Newmont Gold Mine. No deployment has been conducted there yet, but access has been granted by the companies, if needed.

7. THE TWENTYMILE COAL MINE, CO

The Twentymile Coal Mine, located near Oak Creek, CO, is operated by Cyprus Twentymile Coal Company. It is a long-wall mine [24]. In October 1994 it held the

world record for monthly production in an underground coal mine with 546,00 tons [25]. The Cyprus Company has produced a very good video describing the underground operations [26]. This type of mine is of interest in a CTBT verification regime because as the long wall advances the mined-out area collapses behind the face. That collapse may send out seismic signals strong enough to be picked up by an International Monitoring System. Also, if large collapses can be controlled they may provide an opportunity to conceal a small nuclear explosion in another part of the mine property [9,14]. From an on-site inspection point of view it is interesting to find out whether any features at the ground surface will reveal the existence of underground collapses behind the longwall face.

So, starting in July 1995 LLNL deployed a seismic network to listen to collapses generated by the opening of a new mine panel. In early October, as the 250 m (800 ft) wide face had advanced about 600 m (2,000 ft), an overflight of the area was made. The underground location of the new panel is shown as an overlay on Figures 18 to 23.

The overall mine site is shown in Figure 18, which is taken looking West from about 1,200 m (4,000 ft) above the mine surface. The massive rock bed in the mesa structure continuing in the distance to the other mesa is the Twentymile sandstone. For elevation scale, the altitude difference between the road and the top of the mesa to the right is about 200 m (700 ft). The working coal face is moving toward the viewer, and at the date of the picture the position of the face, underground, was at the dashed line. In Figure 19, looking South, the face is coming from the right and in Figure 20, looking North, it is coming from the left.

A close-up of the middle portion of the panel, between the two mesas, is shown in Figure 21, looking South. The panel will pass North of the dark line. The underground face has not reached that area yet. The East end of the panel location is shown on Figures 22 and 23.

The ground surface of the mesa to the West (Figures 19, 20) did not reveal any activity from underground, even though some rock beds underground had already collapsed behind the face supports. The aerial survey can be repeated after the extraction of the 6,000 m (20,000 ft) long panel is complete. The mining of a previous panel to the North of the current one was responsible for fracturing and collapse of a part of the cliff in the Twentymile sandstone. This is shown from the air in

Figure 24 and from the ground in Figure 25. The large block in the foreground of Figure 25 is the size of a car.

8. THE SOLVAY MINE, WY

The area surrounding Green River, WY is leading the world in the production of trona, from which soda ash is produced [27]. Typically, the mining is by the room-and-pillar method [28], at depths ranging from 240 to 520 m (800 to 1,700 ft). The extraction ratio is typically 50%.

In February 1995 the trona mine, operated by Solvay Minerals 25 km (16 miles) Southwest of Green River, WY, was the site of a very large collapse of pillars. It is estimated that the collapsed area, 480 m (1,600 ft) underground, was 1.9 km² (20×10^6 ft² or 0.75 square mile), and the underground closure was about 3 m (10 ft). That collapse generated a seismic event of local magnitude $M_L=5.1$ [10].

One would certainly expect such an event to be recorded by the International Monitoring System and to raise some questions regarding its origin. A surface inspection of the site may be requested. As it turned out, the ground inspections conducted by Solvay Minerals personnel revealed not a trace at the surface of this very large underground collapse, even though surface surveys indicated a subsidence of up to 1 meter. We also performed an air-photo survey of the site in October 1995. The outline of the subsurface caved area is shown as an overlay on Figures 26 to 29.

Figure 26, looking Southwest, and Figure 27, looking South, give an overview of the site. Figure 28, looking North, does not reveal any disruption of the ground, or any trace across the roads. Figure 29, a close-up, taken at about 600 m (2,000 ft) above ground, confirms the absence of any indication that could help pinpoint the location of the underground collapse. This is in sharp contrast to the highly visible scarps observed at the San Manuel Mine site. It is also a useful caveat for future verification procedures. However, in an actual on-site inspection one would look for additional indices. One can be found a Solvay: the North wall of the berm for the settling pond did breach. The white area going towards the plant corresponds to the spill of fluids from the pond. This anomaly should be noticed in an OSI.

9. SUMMARY AND COMMENTS

The DOE and National Laboratories involved in CTBT verification have enjoyed an outstanding cooperation from several U.S. mining companies to allow field deployments and inspections at their sites. Beside their success at characterizing the signatures of various mining operations, which is important for CTBT monitoring, these activities have provided the following insights for future monitoring and on-site inspections.

- the work at the Henderson Mine revealed how difficult it is to locate highly emergent mine collapse events
- the visit of the San Manuel Mine showed very clear surface expressions of underground caves
- the monitoring of Black Thunder explosions revealed the ground coupling differences between shots in waste rock, having an open face, and confined shots in coal
- the deployment at the Newmont Gold Mine gave a good seismic calibration of mine shots in metamorphic rocks involving a few 100,000 lbs of ANFO
- the aerial surveys and ground surveys at the Twentymile Mine and the Solvay Mine showed examples of surface expressions of underground collapses such as cliff failures and liquid spills; but they also showed that large areas of ground surface may be unaffected by the subsurface closures

These experiences have led to additional research concerning event location, and they will also be useful in the development of inspection procedures and in the training of inspectors.

10. PHOTO SECTION

Figure 1: Aerial view of Red Mountain, CO and the Henderson and Urad "glory holes" (courtesy Cyprus Climax Metals Company).

Figure 2: Henderson Mine, CO, mine shaft and surface structures.

Figure 3: The Henderson "glory hole" from the mine buildings

Figure 4: Red Mountain from a seismic station, 10 km to the West.

Figure 5: Site of an LLNL seismic station on the North side of Red Mountain (courtesy A. Smith, LLNL).

Figure 6: An ore draw point at Henderson (courtesy A. Smith, LLNL).

Figure 7: A front-end loader dumping in an ore pass at Henderson (courtesy A. Smith, LLNL).

Figure 8: The open pit and head frames at the San Manuel Mine, AZ.

Figure 9: Surface of the cave area at the San Manuel Mine, AZ.

Figure 10: The coal seam in one of the open pits, Black Thunder Mine, WY

Figure 11: The pit of Figure 10, from the North end, at Black Thunder, WY.

Figure 12: Open-cast blast pattern ready for firing, at Black Thunder.

Figure 13: The pit of Figure 10, after a 3.6-million lbs. ANFO cast-blast, Black Thunder, WY.

Figure 14: Air view of the Newmont Gold Quarry, NV, looking North.

Figure 15: The Newmont Gold Quarry open pit, looking Southeast.

Figure 16: The Newmont Gold Quarry site, looking North.

Figure 17: The Barrick Goldstrike, NV, open pit, looking Southeast.

Figure 18: Overview of the Twentymile Mine site, CO, looking West.

Figure 19: Twentymile site, looking South. West and East mesas, and trace of new underground panel, no. 9.

Figure 20: Twentymile site, looking North, between the West and East mesas.

Figure 21: Twentymile site, a close-up of the passage between the two mesas.

Figure 22: Twentymile site, the East end of the new panel and surface mine structures.

Figure 23: Twentymile site, East end of the new panel and the cliff in the massive Twentymile sandstone.

Figure 24: A failure in the Twentymile sandstone cliff, viewed from the air.

Figure 25: Twentymile sandstone cliff failure, from the ground.

Figure 26: The Solvay Mine site, WY, looking Southwest. The underground collapse area is outlined.

Figure 27: The Solvay site, looking South.

Figure 28: The Solvay site, looking North, with spillage of pond fluids in the foreground.

Figure 29: Close-up of the surface above the North end of the collapse area at Solvay, WY: no surface indications.

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