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Sinkhole formation in central Victorian alluvial gold mining areas

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ABSTRACT

This paper sets out some observations on sinkholes that have formed during 2010 and 2011 at two sites within central Victoria. The sinkholes appear to be related to alluvial gold workings, dating from the early 1850's to mid 1880's. Historical plans showing the locations of these workings are not available. Some historical mine surveyor reports are available which indicate that abandoned tunnels within alluvial deposits are present at depths of up to 30 m below ground surface and can extend over 100 m from shafts. It is also noted, that early during the Victorian gold rush, efforts were made by miners to deliberately keep new gold finds secret. Typically, the shafts and tunnel entrances have long been backfilled leaving little evidence at ground surface as to the locations of the workings. This combined with the lack of plans makes it challenging to identify the presence and locations of abandoned tunnels, which unlike shafts seem not to be typically backfilled. The alluvial soils comprise clay and silt with minor sand and gravel which can be dispersive. Wet weather, and an associated increase in groundwater infiltration over voids is inferred to have exacerbated the collapse of abandoned tunnels leading to sinkholes forming at the ground surface. In each case, the sinkholes have presented a risk to both life and property. In one case, the sinkhole forced emergency evacuation and eventual demolition of a house. Areas in Central Victoria known to have been subject to alluvial mining and historical mining methods are discussed. Comments are provided on factors considered to have contributed to the formation of sinkholes at two sites, the difficulty in predicting the locations at which they might form and the uncertainty associated with the hazard they present to both life and property.

Keywords: sinkhole, alluvial mining, collapse, abandoned mines.

1 INTRODUCTION

In 2010 and 2011, Victoria experienced above average rainfall and floods following a period of drought. This increased rainfall appears to have triggered the collapse of some abandoned mine workings, leading to sinkhole formation, and presenting a hazard to life and property. Over 40 collapses are reported to have formed in the Bendigo region between September 2010 and April 2011 (Bendigo Advertiser, 13 April 2011). The Victorian 2010-2011 flood recovery report published in November 2011 mentions 12 mining related sinkholes opening as a result of the floods. The authors are also aware of sinkholes forming in the Ballarat, Warrandyte and Alexandra area in 2010, 2011. Some of these are thought to have been caused by subsidence of backfill within abandoned, filled mine shafts. This paper specifically addresses sinkholes formed by the collapse of natural ground over abandoned tunnels.

Gold was first discovered in Victoria at Clunes in July of 1851. (Lett, 1970). Early gold mining from the 1850's through to the 1870's primarily focussed on winning 'free' gold within alluvial deposits. Throughout this time, alluvial goldfields were developed and worked in many of the gullies and creeks of the central Victoria bush (Figure 1). Alluvial gold mining continued in some areas into the 1900's, however, from the mid 1870's, most of the mining was deeper reef mining. Case studies on sinkholes forming in two alluvial gold mining areas, the Alexandra and Caledonia goldfields are presented in this paper, one from Alexandra itself, and one from Strathewen in the north of the Caledonia Goldfield.

In June 1866 gold was first discovered in Alexandra (Smyth, 1869) and by December of that year two alluvial gullies were being worked in the region (Lett, 1970). By the early 1870s much of the shallow alluvial gold had been mined and small scale alluvial mining operations gave way to deeper quartz reef mining.

In 1854 the Caledonia Diggings (around St Andrews) were opened (Lett, 1970). They are known to have extended from the Yarra River in the south to St. Andrews (formerly Queenstown) in the north, and included the area between Diamond Creek in the west and Watson's Creek in the east, with some mining surveyor reports of the time mentioning prospecting in areas to the north of Queenstown, in the vicinity of Strathewen (MSR 1859). The area was worked extensively from the mid 1850s with new rushes occurring up until the mid to late 1860s.

Abandoned gold mine workings are common within Victorian goldfields. The locations of many of the workings have been mapped by the Department of Primary Industries and predecessor organisations, with concentrated efforts to do so in some built up areas such as Bendigo and Ballarat. However, as discussed subsequently, it appears that the locations of some of the early alluvial workings, 1850's to 1880's were either not recorded, perhaps deliberately to maintain commercial advantage at the time, or recorded with non specific location information.

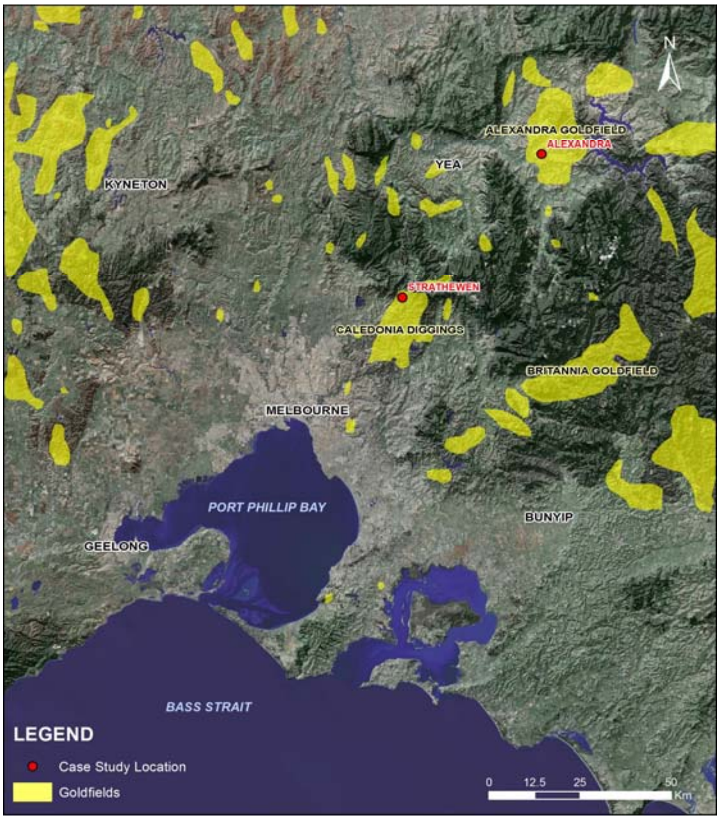

Figure 1. Alluvial Gold Mining Areas, Central Victoria (adapted from Letts, 1970)

2 ALLUVIAL GOLD MINING IN VICTORIA, 1851 TO MID 1880'S

The following discusses two common methods by which alluvial mining was undertaken in Victoria between 1851 and the mid 1880's.

2.1 Surfacing and Shallow Sinking

News of a gold discovery would spread quickly and it did not take long after an initial strike for miners to populate an area. Inhibited by both access and finances, early miners were restricted to bringing with them limited tools to a new dig. (Smyth, 1869) This accompanied with the fact that deep leads and quartz veins were often as yet undiscovered, early miners were content to initially mine the gold rich alluvial soils near the ground surface.

"Shallow sinking" was the process by which many new rushes were initially worked. Miners would excavate into alluvial material in the sides of valleys or creek beds. Tunnels would either be advanced directly into the sides of creek beds, or shafts sunk (typically less than 10 m) until gold bearing material was found (Smyth, 1869). Tunnels may then have been driven from the shallow shaft.

Typically, gravel beds or channels, termed 'leads' were targeted where the heavier alluvial gold was concentrated. Some leads could have multiple tunnels in them as the miners attempted to chase gold rich beds. If required, ground support was provided using timber lagging. However, more often than not, tunnels were unsupported and abandoned as quickly as they were sunk after the lead was presumed to be exhausted (MSR, 1959).

Considering this style of ad-hoc mining and the intensity with which it was administered, one can imagine the state in which the goldfields were left. Whilst most tunnel and shaft entrances have at some stage been filled in, it appears that generally no attempt was made to backfill tunnels.

Although some records were kept detailing gold mining in Victoria, accurate mapping of early mines (pre 1870's) is difficult to come by, and in many cases seemingly does not exist. Limited records as well as the likelihood that some mining would have been conducted without the knowledge of mining surveyors means that whilst the general vicinity where alluvial mining occurred is known, the exact locations of shafts and tunnels is not.

Figure 2 is a schematic showing the shallow sinking alluvial gold mining method.

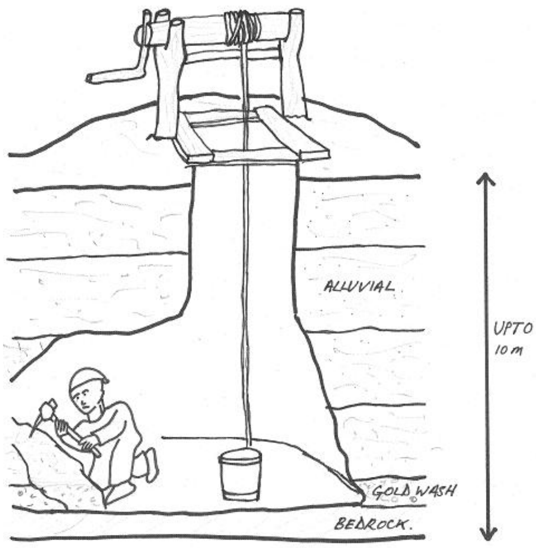

Figure 2. Shallow Sinking, (adapted from Swift, 2010)

2.2 Deep Lead Alluvial Mining

"Deep lead" is a term used to refer to an alluvial deposit of auriferous gravel that has been transported by a drainage system that is no longer present and now lies at significant depth due to the deposition of overlying materials.

Davey and McCarthy (1988) states that the deep lead mining technique used in the Victorian goldfields was developed specifically for alluvial materials, comparable to no other mining techniques at the time. In the early 1850's the process was fully manpowered, and it was not until the late 1850's that horse driven puddling processes and steam powered pumping were involved.

Deep lead mining is the process of sinking a shaft to depth until gold bearing alluvial material is encountered (a "lead") and then driving tunnels along the lead laterally, recovering auriferous gravel for surface processing. The method is similar to shallow sinking, however shafts are typically much deeper and the mining less ad-hoc. Shafts were excavated by hand, sometimes to considerable depth. In the Alexandra area, shafts of up to 30 m depth, all through alluvium are recorded (Grieg, 1872). Deeper shafts are recorded in the Ballarat and Bendigo areas where the deep leads were often overlain by basalt (Davey, 1996).

The first shafts to be sunk in the Victorian goldfields were in the early 1850's and the first supported shafts were sunk in late 1852 (Davey, 1988). By March 1853, shafts were typically supported by timber slabbing (Davey, 1988). Support for the tunnel drives, some exceeding 100 m in length, varied depending on ground conditions. In some drives the roof consisted of clay and was self-supporting. Where sands or gravels in the tunnel roof required support, post and slab construction was used in most instances. In a worst case scenario the whole drive required slabbing, similar to shaft construction. In mining areas where timber was scarce, once a drive had been abandoned supporting slabs were withdrawn. Sheet iron caissons for support shafts were trialled in 1855 but failed due to lack of strength (Davey, 1988).

Water inflow was also a significant problem in the mining of a deep lead. Davey (1988), states that baling water from shafts by hand before entry could take up to eight months.

Figure 3 is a schematic indicating the methods by which deep lead mining was undertaken.

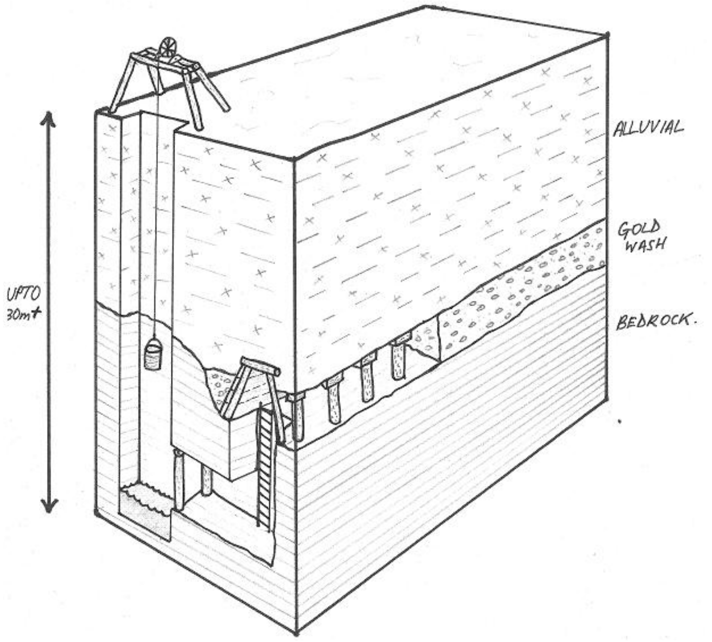

Figure 3. Deep Lead Mining (adapted from Kaufman, 2010)

3 SINKHOLE FORMATION RELATED TO ALLUVIAL MINING - CASE STUDIES

The review of early alluvial gold mining methods set out above suggests that abandoned, unsupported tunnels within alluvial material could be present in alluvial gold mining areas at depths of up to 30 m. The specific locations and extents of such underground workings particularly early workings is largely unknown. These workings now present a hazard through ground subsidence and sinkhole formation as described in the case studies below.

3.1 Alexandra

Following heavy rainfall in late June and early July 2010, a sinkhole formed rapidly beneath the corner of a single storey residential building, within close proximity to a downpipe which was reported to be discharging water directly on to the ground. The sinkhole had a diameter and depth of about 5 m after formation, undermining and leaving the corner of the house slab cantilevered about 2.5 m over the hole. Loose collapse debris was observed in the base of the sinkhole, however tunnels or drives extending off the sinkhole were not visible from the ground surface. Due to safety concerns the house was evacuated and has subsequently been abandoned.

A drilling program at the site indicated that the material in which the sinkhole formed is very stiff silty clay with minor gravel, overlying bedrock at a depth of 11.5 m. Laboratory testing on the alluvial material indicates that it is typically dispersive. The permanent groundwater table was measured below the level of the sinkhole. However, perched groundwater was present within the sinkhole itself.

A search of mining records for Alexandra indicated that there was extensive alluvial mining undertaken in the area. Although no records showing specific tunnel or shaft locations in the vicinity of the sinkhole were obtained. The records described deep lead mining methods in the same street, whereby shafts were sunk to bedrock (up to 25 m depth) and leads at the base of alluvial deposits exploited (Grieg, 1872). There are several other anecdotal accounts of sinkhole formation in the area. However, sinkholes are not widespread as might be expected if they were formed through a natural process, for example as might be observed in karstic terrain.

3.2 Caledonia Goldfield, Strathewen

Following heavy rainfall events in early 2011, sinkholes formed in and around the Strathewen Sporting Complex, an open recreation area with playground and sporting ovals. The site is underlain by alluvial material which extends west up a valley into private farmland. The area is mostly cleared land with some trees. Although the vegetation is now recovering, vegetation through this area was extensively destroyed during the February 2009 Black Saturday Bushfires.

Seven clearly delineated sinkholes were observed during a site walkover and several that appeared to be in the process of forming. Although the sinkholes varied in shape and size, they were typically about 2.0 m deep with diameters between 0.5 m and 7.0 m. Water was also observed at the base of some of the sinkholes. Surface drainage at the site is such that it is directed towards the areas in which the sinkholes formed. The volume of surface water runoff may be exacerbated by the lack of vegetation in the area.

The materials observed in and around the sinkholes consisted of clayey silt, with some gravel. The natural soils observed during the investigation are consistent with alluvial materials.

A search of mining records yielded reference to alluvial mining in creeks within the areas around Strathewen, but no specific records of alluvial mining in the vicinity of the Strathewen Sporting Complex (MSR 1859). The sinkhole formation appears to be localised and given the relatively shallow depth of the sinkholes, may be related to shallow sinking type alluvial mining associated with the Caledonia Goldfield.

3.3 Remediation

In both cases, the sinkholes were backfilled with a free draining, non dispersive aggregate and capped near surface with a low permeability compacted clay material. Surface drainage measures were also implemented to reduce the propensity for surface water to concentrate and infiltrate in the vicinity of the sinkholes.

4 SUGGESTED MECHANISM FOR SINKHOLE FORMATION

Subsidence of loose material that has been used to backfill mine shafts is a common cause of sinkhole formation in Victorian mining areas. However, in both of the case studies described here, the sinkholes appear to have formed through natural ground. Both have the following features in common:

- Ground comprising dispersive alluvial clays and silts with minor sand and gravel, as would be expected for a material transported in water and deposited in a fluvial or floodplain environment.
- Both sites are underlain by voids. Sinkholes are localised within the area, suggesting the voids are probably not the result of natural processes. They are inferred to have been formed by alluvial mining, likely associated with tunnels rather than shafts between 1850 and 1875.
- The voids are higher than the permanent groundwater table.
- Surface water concentrates and infiltrates at the locations where the sinkholes formed.
- The sinkholes formed during a wet period following a period of drought.

It is apparent that surface water infiltration is a key factor in triggering the sinkhole formation. In both cases, the voids are inferred to be above the groundwater table, and wetting of unsaturated, dispersive soils overlying voids appears to have triggered the formation of the sinkholes. In addition to the saturation of the ground overlying the voids, the dispersive characteristics of the alluvial soils may also have exacerbated the problem. As water infiltrates vertically into the ground and into the void, the roof of the void may be eroded, expanding the void upwards. Material eroded then collapses into and redistributes along the void. In the case of the Alexandra sinkhole, material dropped 5 m. Typically, tunnel voids associated with alluvial mining may have been expected to be up to 2 m in height, raising the possibility of expansion of the void due to erosion and dispersion of the alluvial materials.

Figure 4 presents a schematic illustrating the suggested mechanism of sinkhole formation.

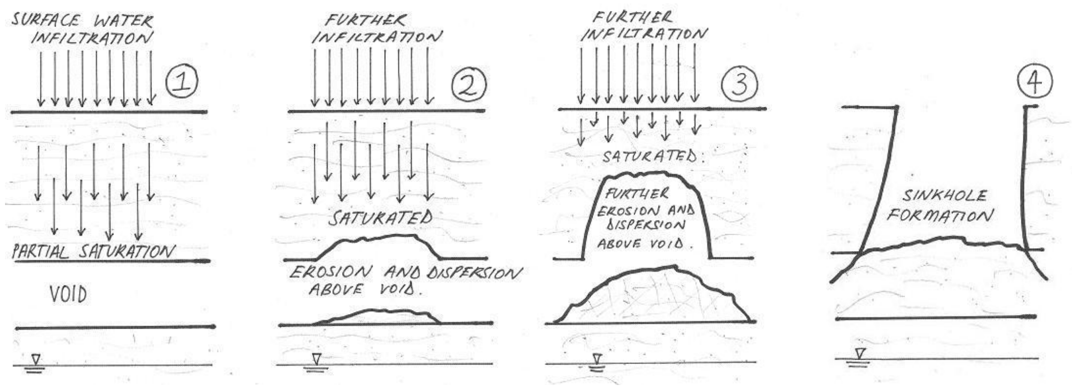

Figure 4. Suggested Mechanism of Sinkhole Formation

5 CONCLUSIONS

Between 1851 and the mid 1880's, areas of Central Victoria were subject to extensive alluvial mining, typically, but not exclusively within the vicinity of surface watercourses. The mining of 'leads' was relatively ad-hoc, with mines rapidly excavated and subsequently abandoned. Tunnels may extend over 100 m in partially saturated alluvial material. With saturation of the ground, collapse of material into sinkholes can be rapid, presenting a significant risk to life and property.

The lack of records describing the locations of the alluvial gold workings, makes management of these risks difficult. In the case studies described here, collapse of the sinkholes was triggered by an unusual concentration of surface water, exacerbated by the dispersive nature of the alluvial soils overlying the void. For development in areas that could be underlain by voids, whether specific void locations are known or not, management of surface water runoff to prevent water ponding and infiltration in the vicinity of buildings is considered a key factor of risk management.

Investigation in areas known to have been subject to alluvial gold workings, may need to address the risk of underground voids, through, for example, deeper drilling than may normally be required for foundation considerations alone. For important structures or intensely mined areas, active searching for voids through (for example) probe drilling or geophysical methods may be warranted.

In the case studies described here, backfilling of sinkholes with a free draining, non dispersive aggregate was found to be a practical and successful means of remediation. This, combined with drainage improvements, ongoing monitoring and consideration of the possibility of underground voids in planning for developments are suggested methods for management of the sinkhole risk.

6 ACKNOWLEDGEMENTS

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REFERENCES

Bendigo Advertiser (13 April 2011), "Collapsed Bendigo mines proving costly", Fairfax Media
Davey, C.J. (1996). "The origins of Victorian mining technology, 1851 – 1900." The Artefact, Melbourne.
Davey, C.J. and McCarthy, P.L. (1988). "Deep lead mining in Victoria." Second AusIMM Mineral Heritage Seminar, Sydney
Department of Natural Resources and Environment, (June 1999). "Historic Gold Mining Sites in St Andrews Mining Division."
Department of Planning and Community Development, "St Andrews – Caledonia Goldfield Notes." <http://www.dpcd.vic.gov.au/>
Department of Planning and Community Development, "Alexandra Goldfield." <http://www.dpcd.vic.gov.au/>
Grieg, W. S. (1872). "Mining Surveyors Report, Alexandra Subdivision, March 1872."
Kaufman, R. (2010). "Underground Deep Lead Mining." Egold, <http://www.egold.net.au/> (Jun. 22, 2011)
Lett, J. (1970). "The History of Gold Discovery in Victoria." The Hawthorn Press, Melbourne.
Lock, A.G. (1882). "Gold: Its occurrence and extraction." E. & F. N. Spon, New York
Mining Surveyors of Victoria. (1859). "Mining Surveyors Reports: No. 6 October 1959." W Fairfax and Co Printers and Publishers, Melbourne
Murphy, J. (1862). "Mining Surveyors Reports (St Andrews Division)." Vol 1861:Jan – 1861: Dec, Victoria Board of Science, Victoria Mines Department.
Smyth, R.B. (1869). "The Goldfields and Mineral Districts of Victoria." Poppet Head Press, Melbourne.
Swift, A. (2010). "Underground Deep Lead Mining." Egold, <http://www.egold.net.au/> (Jun. 22, 2011)
Victorian Government (2011). "Victorian Floods 2010-2011 Recovery Progress Report 2011", Victorian Government, Melbourne