Preliminary Survey Report for Jagersfontein

Orthophotos, Topographic Surveys (DEM), and Reconstructed Surfaces Produced from Archive Satellite Imagery

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Better Data for Better Decisions

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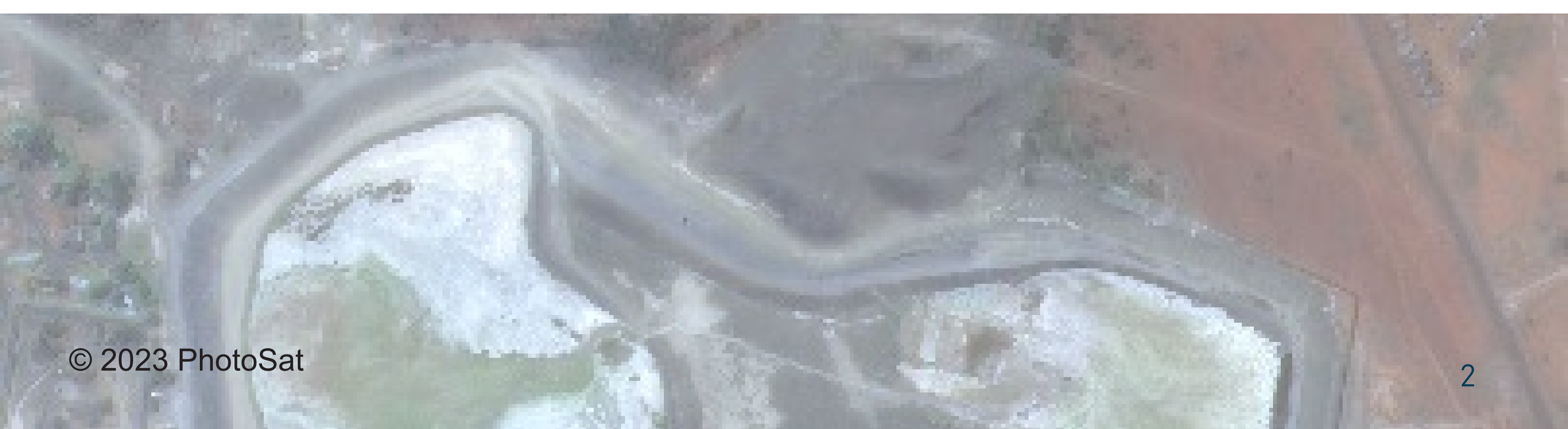


Report Disclaimer

This report does not constitute Engineer or Geoscientist advice.

Contents

List of Tables

List of Figures

Introduction

This case study is an illustrative example of how satellite imagery from a variety of archives can be gathered and processed to provide historical survey data.

Background

On September 11, 2022, the tailings storage facility (TSF) at Jagersfontein Tailings Dam suffered a structural failure. The resulting outflow led to significant damage to local infrastructure and resulted in multiple injuries and deaths.

Case Study

Using available archive imagery, this case study was independently produced by PhotoSat following the dam failure at Jagersfontein. No site visit was required to produce this study.

Preliminary results from this study show that approximately 5,040,000 cubic meters of material was released (page 23).

Methodology

PhotoSat uses proprietary deep learning technology, based on geophysical data processing systems, to produce topographic surfaces from stereo satellite imagery.

Archive Satellite Imagery

PhotoSat works with data from many different high-resolution optical satellites. This technology can be applied to both new and archive satellite images.

A search of available archives yielded a large number of usable satellite images. The satellite images cover the Jagersfontein TSF area, and the dates of collection range from the 1970s to near present day. The images shown in this report come from Keyhole, Landsat, Sentinel, and WorldView satellites.

Stereo Pairs

When the satellite captures two or more images of the same area from different angles, it makes it possible to produce ground elevation measurements. These image combinations are called stereo pairs. (Fig. 1)

PhotoSat uses stereo pairs collected by high-resolution optical satellites for this process, and this results in highly accurate ground elevation measurements. Ideally, the individual images are captured less than a minute apart to ensure continuity in the data. However, stereo pairs can be formed by combining suitable images from different dates as well.

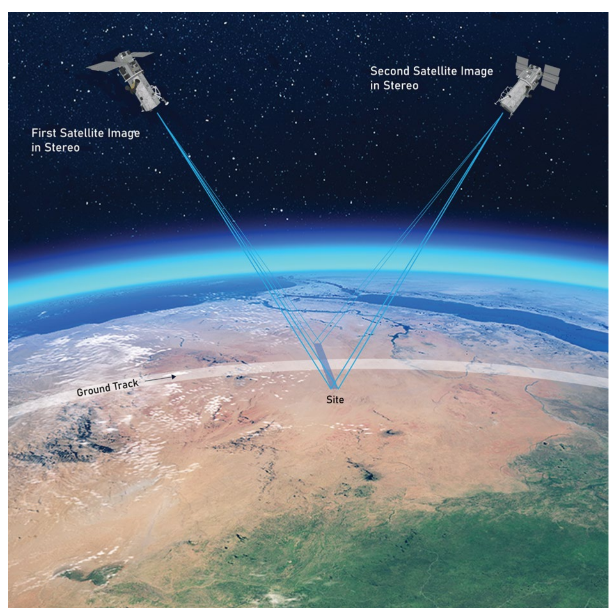


Figure 1: Area being captured in stereo

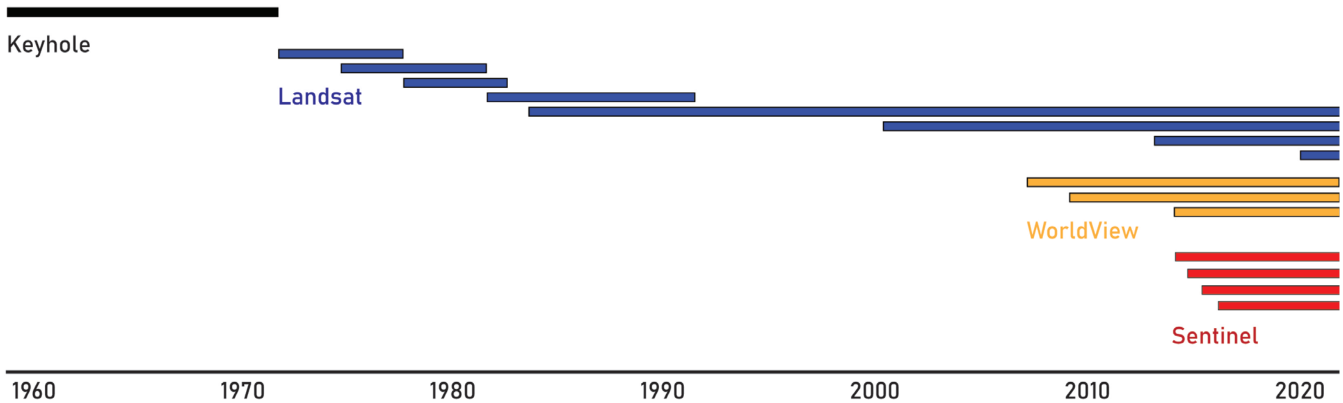


Figure 2: Timeline of selected satellite missions

Satellite Sources

This report is based on imagery collected by different types of satellites. (Fig. 2)

Keyhole

Between 1959 and 1972, more than a dozen optical satellites were launched for the purpose of Cold War surveillance. Some of the satellites collected stereo imagery with spatial resolutions as small as 0.61 m. These archives were declassified in 1995.

Landsat

The first Landsat was deployed in 1972. These satellites collect mono imagery at 30 m or 15 m ground resolution.

WorldView

WorldView (WV) imagery used in this report is courtesy of Maxar Technologies.

WV-1 collects imagery at a ground resolution of 50 cm, in greyscale. Individual scenes from WV-1 can be colourized (Fig. 3) by augmenting the image using other suitable satellite images.

WV-2 and WV-3 collect in colour. WV-2 has a ground resolution of 50 cm while WV-3 has a ground resolution of 50 cm or 30 cm.

Sentinel

The first Sentinel was deployed in 2014. These satellites collect mono imagery at a 10 m ground resolution.

Figure 3: Greyscale and colourized WV-1 satellite image

Results

Preliminary results show that approximately 5,040,000 cubic meters of material was released (page 23).

Archive Search Results

A search of available archives yielded four separate sets of stereo pairs, with dates ranging from 1977 to 2022.

In addition to stereo pairs, 23 mono satellite images were found in the satellite archive. Although it is not possible to directly produced elevation surveys (DEM) from mono images, these images show the condition of the ground and are valuable as part of the record.

The images used in this report are shown in chronological order in Appendix A.

Surfaces (DEM) by Year

Four topographic surfaces were made from stereo pairs, and one surface was reconstructed. (Tab. 1)

Topographic Surfaces from Stereo Images

From each stereo pair, a topographic surfaces (DEM) was generated. Visible geotechnical boundaries of the dyke, tailings, and supernatant ponds were generated.

The data was used to measure:

- Placement volumes, height, and location on an iterative surface to surface basis
- Measurement of embankment wall height
- Vertical distance between the contained tailings and the spillway elevation
- Vertical distance between the point where tailings contact the dyke wall and the upstream shoulder of the dyke wall at that location
- Comprehensive wall height along the upstream crest of the dam

Image 1 - Date	Image 2 – Date	Satellite(s)	Resolution
February 4th 1977	February 4th 1977	Keyhole	60 cm-120 cm
February 26th 2011	March 9th 2011	Worldview-2 & Worldview-1	50 cm
October 19th 2017	October 19th 2017	Worldview-1	50 cm
September 6th 2022	n/a	Sentinel 2A	10 m
September 16th 2022	September 24th 2022	Worldview-2	50 cm

Table 1: List of satellite images used for producing surfaces

Reconstructed Surfaces

By applying PhotoSat's reconstruction process to the post-failure survey (Fig. 5) and Sentinel 2A imagery from September 6th 2022, a pre-failure surface was generated.

Based on the existing topographic surface data, the width of the dyke crest and the upstream slope could be determined to re-construct the damaged embankment structure. The September 6th 2022 Sentinel 2A imagery (Fig. 4) was then used to establish the eastings and northings of the tailings footprint within the TSF prior to failure. The elevation of that boundary can then be determined wherever it contacted the re-constructed upstream dyke wall.

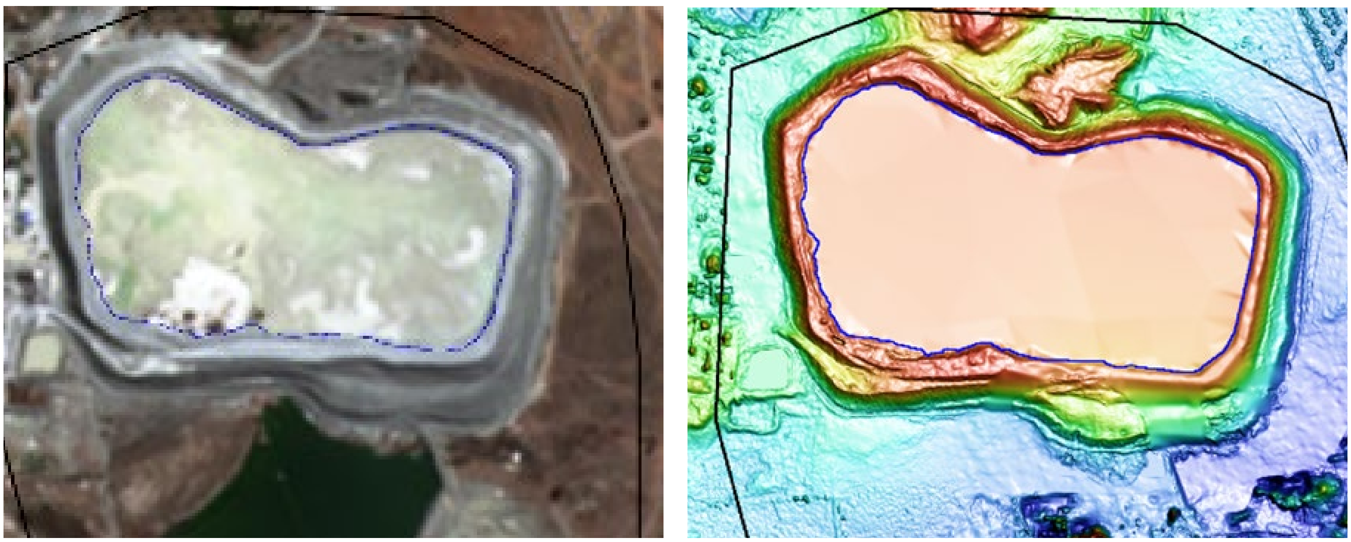


Figure 4: Sentinel 2A satellite image for September 6th with topographic surface

Figure 5: WV-2 satellite image for September 16th/24th with topographic surface

1977 Topographic Surface and Orthophoto

This orthophoto (Fig. 6) shows the Jagersfontein TSF in 1977.

Shown below (Fig. 7) is a 3D topographic surface with segregated components with 1m contours and footprint of the 2022 TSF overlayed. Areas of high moisture tailings were determined using spectral analysis cross-referenced with optical observations.

Figure 6: Keyhole satellite image from February 4th 1977

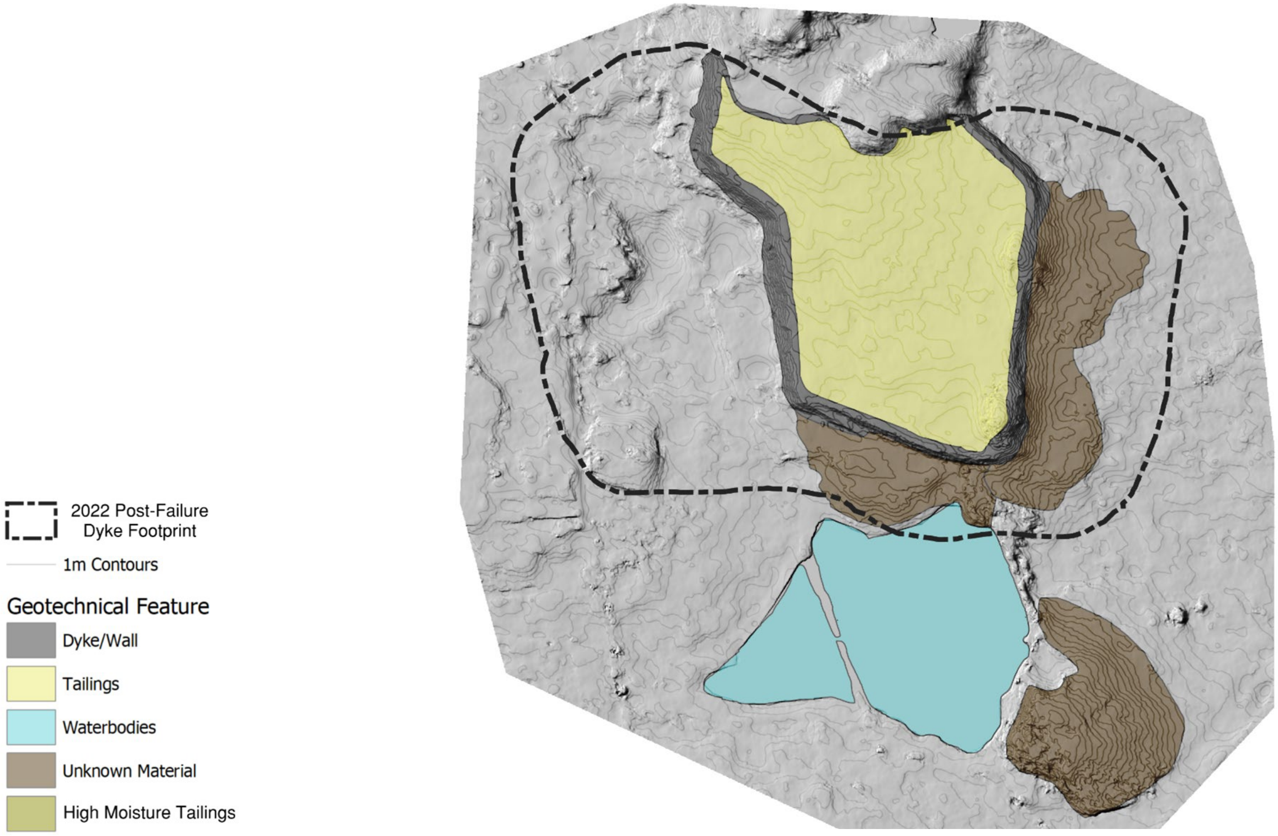


Figure 7: Component map for February 4th 1977

2011 Topographic Surface and Orthophoto

This orthophoto (Fig. 8) shows the Jagersfontein TSF in 2011.

Shown below (Fig. 9) is a 3D topographic surface with segregated components with 1m contours and footprint of the 2022 TSF overlayed. Areas of high moisture tailings were determined using spectral analysis cross-referenced with optical observations.

Figure 8: WV-2 Satellite image from February 26th 2011

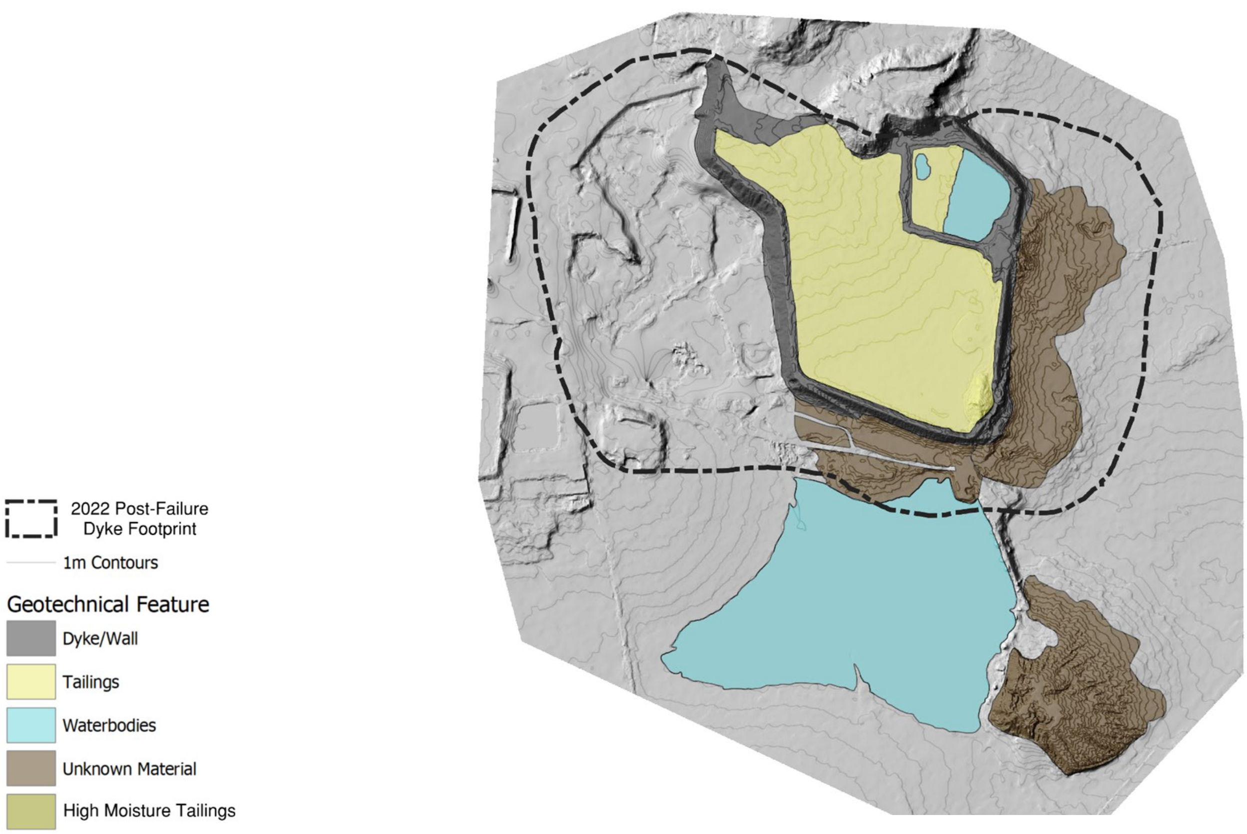


Figure 9: Component map for February 26th and March 9th 2011

2017 Orthophoto and Topographic Surface

This orthophoto (Fig. 10) shows the Jagersfontein TSF in 2017.

Shown below (Fig. 11) is a 3D topographic surface with segregated components with 1m contours and footprint of the 2022 TSF overlayed. Areas of high moisture tailings were determined using spectral analysis cross-referenced with optical observations.

Figure 10: WV-1 Satellite image from October 19th 2017

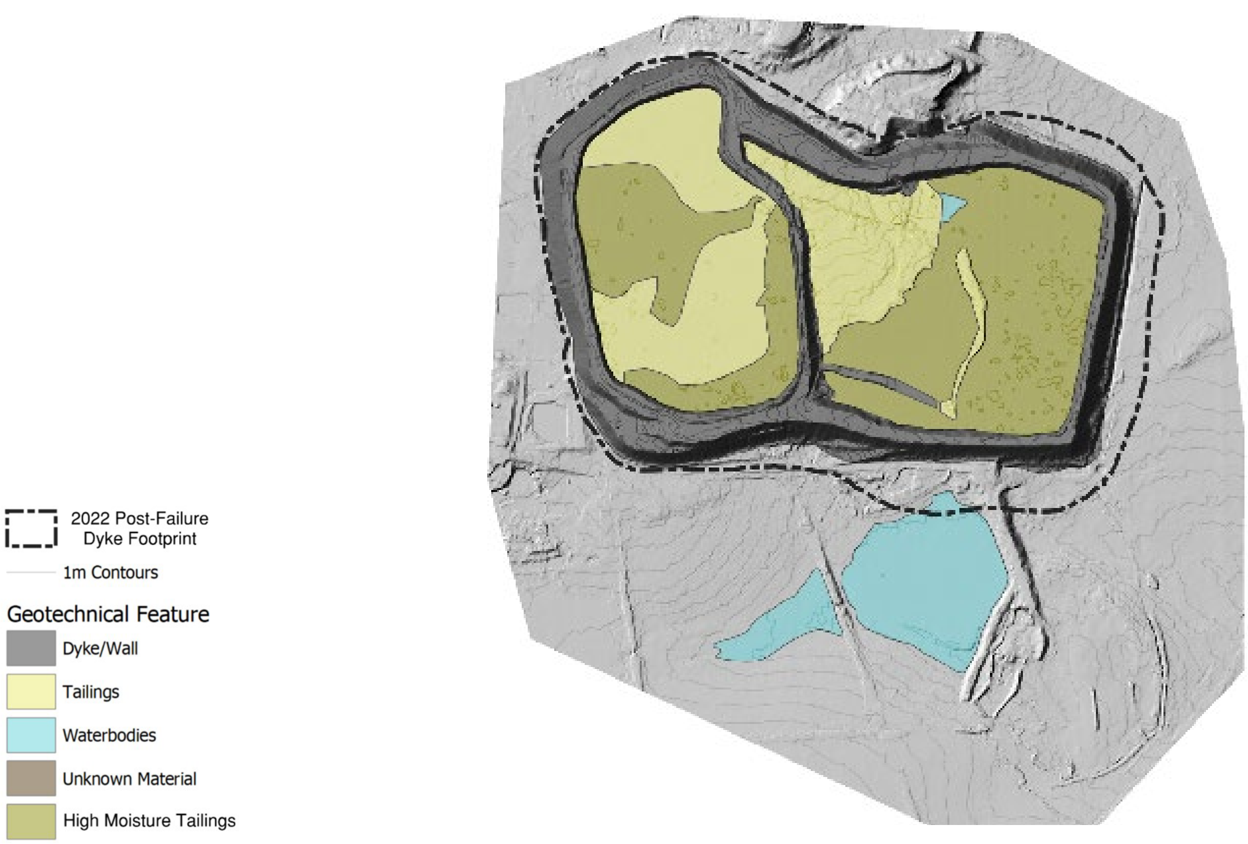


Figure 11: Component map for October 19th 2017

2022 Orthophoto and Reconstructed Surface

This orthophoto (Fig. 12) shows the Jagersfontein TSF in 2022.

Shown below (Fig. 13) is a 3D topographic surface with segregated components with 1m contours and footprint of the 2022 TSF overlayed. Areas of high moisture tailings were determined using spectral analysis cross-referenced with optical observations.

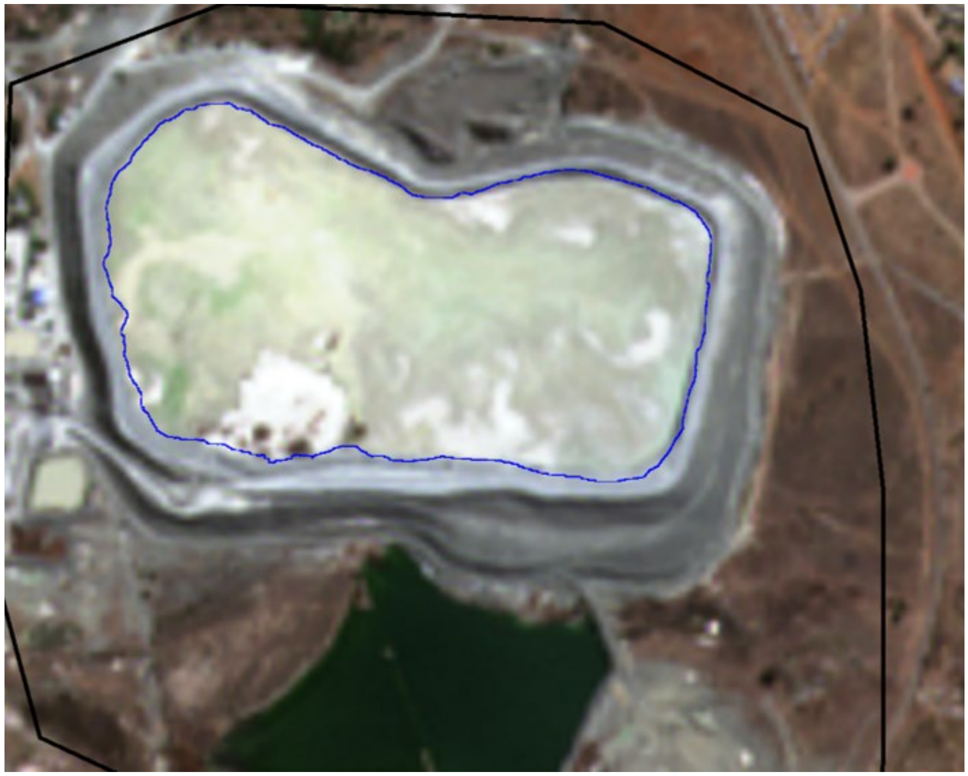


Figure 12: Sentinel 2A satellite image from September 6th 2022

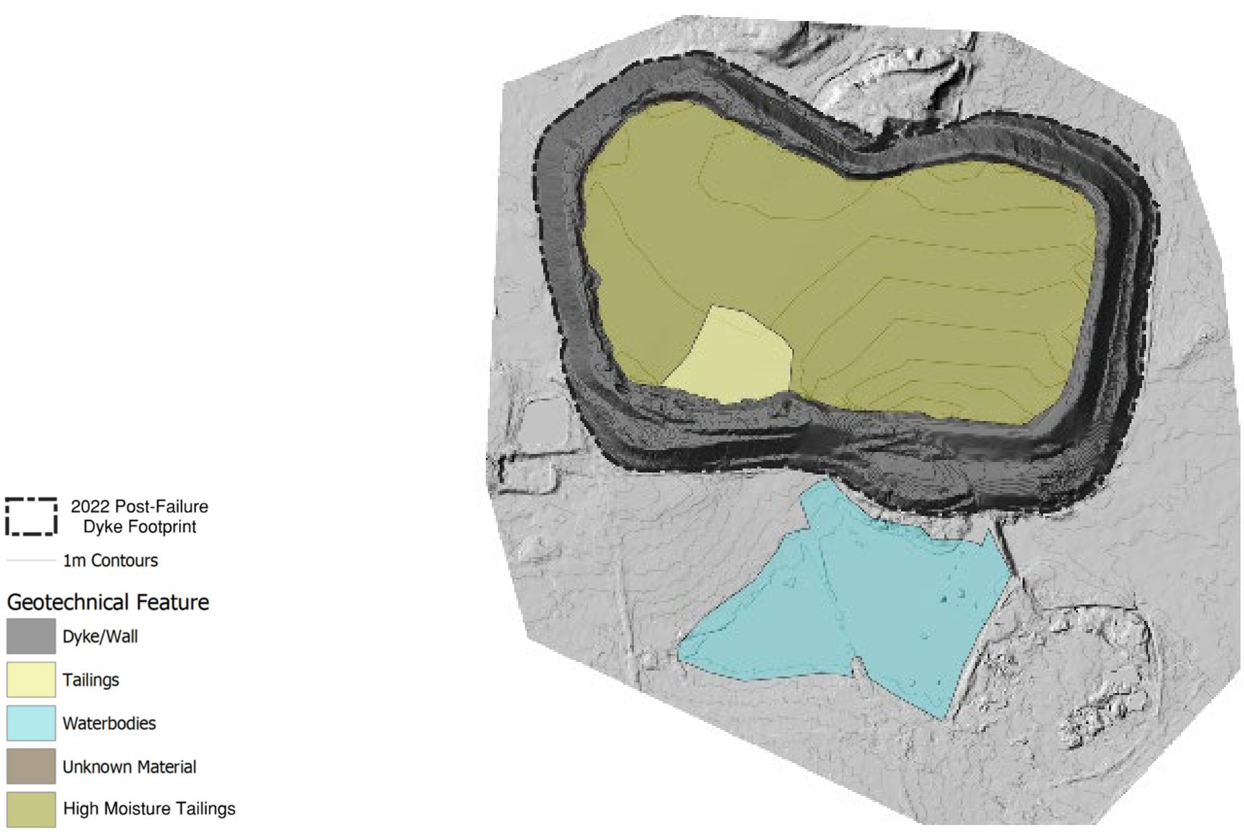


Figure 13: Component map for September 6th 2022

2022 Post Collapse Orthophoto and Topographic Surface

This orthophoto (Fig. 14) shows the Jagersfontein TSF in 2022, five days after the collapse.

Shown below (Fig. 15) is a 3D topographic surface with segregated components with 1m contours and footprint of the 2022 TSF overlayed. Areas of high moisture tailings were determined using spectral analysis cross-referenced with optical observations.

Figure 14: WV-2 satellite image for September 24th 2022

Figure 15: Component map for September 16th and September 24th

TSF Cross Sections

Eleven cross-section locations (Fig. 16) were selected to visualize the evolution of the tailings storage facility from 1977 to 2022. These cross sections (Fig. 17 to Fig. 27) show the elevation profiles from the four topographic surveys and one reconstructed surface.

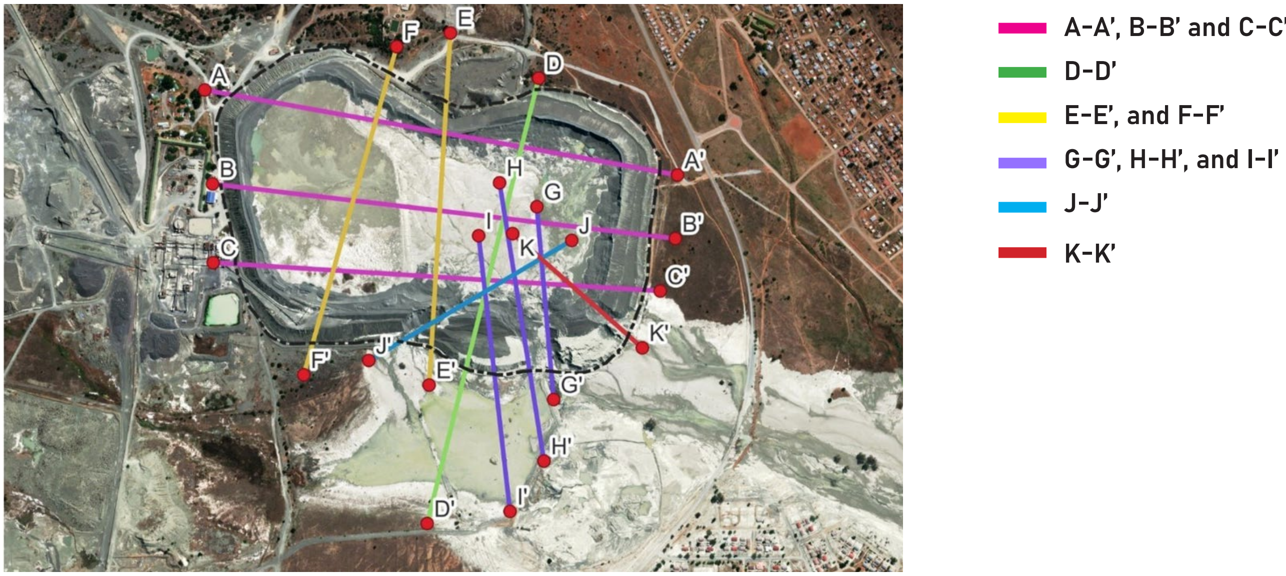


Figure 16: Cross-section layout

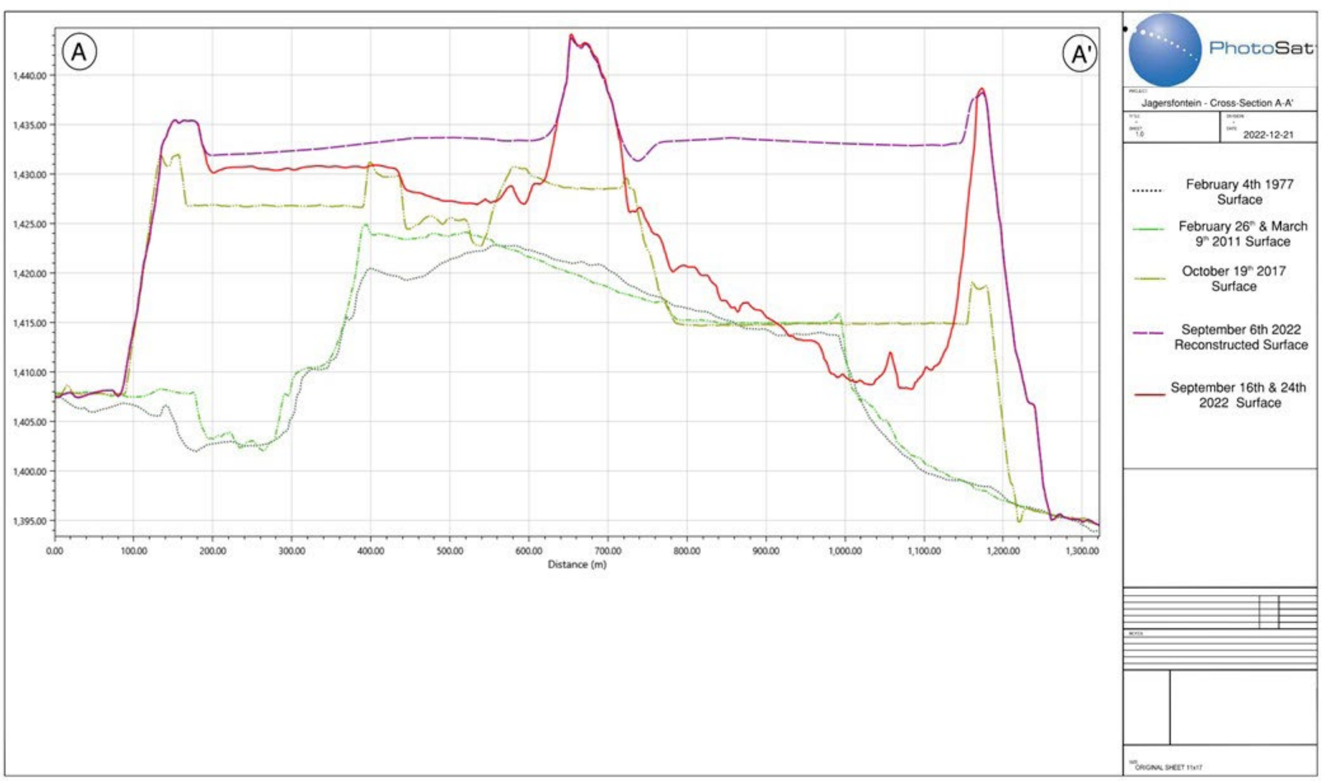


Figure 17: Profiles at cross-section A

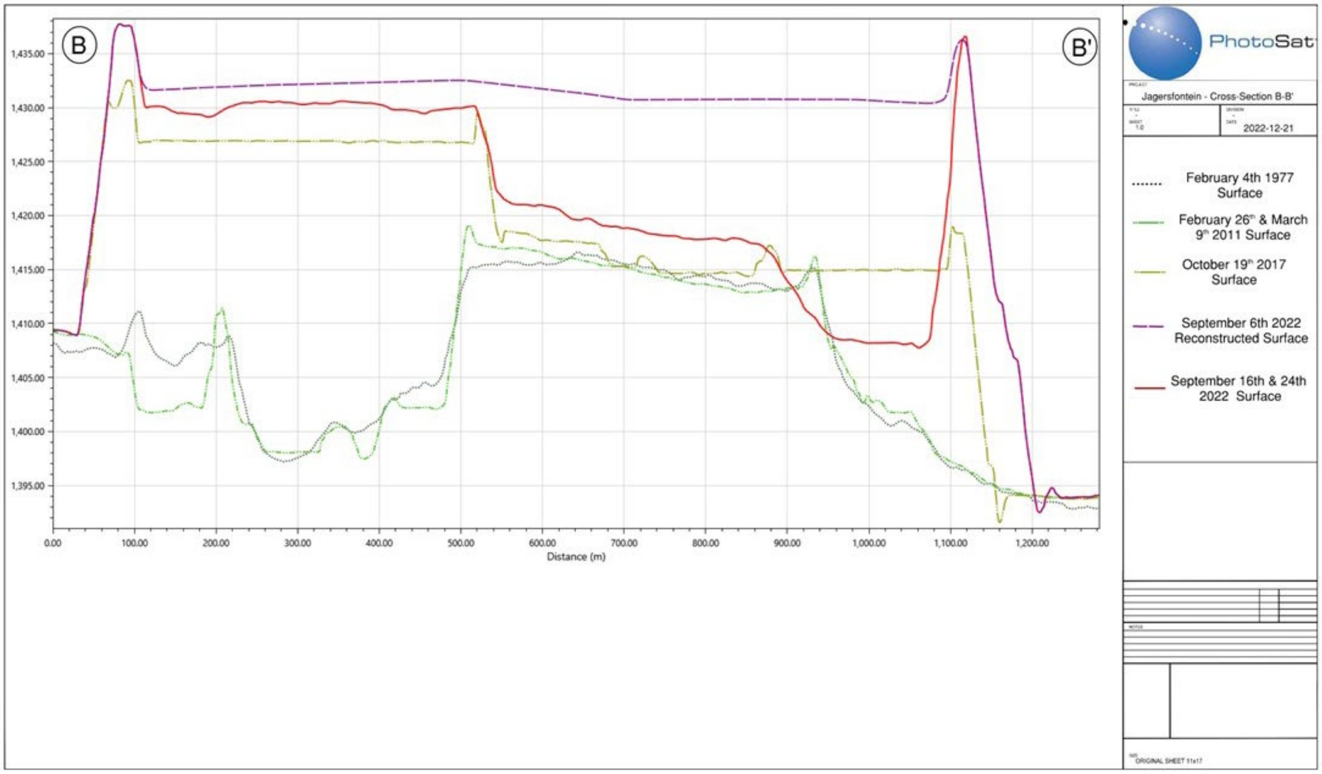


Figure 18: Profiles at cross-section B

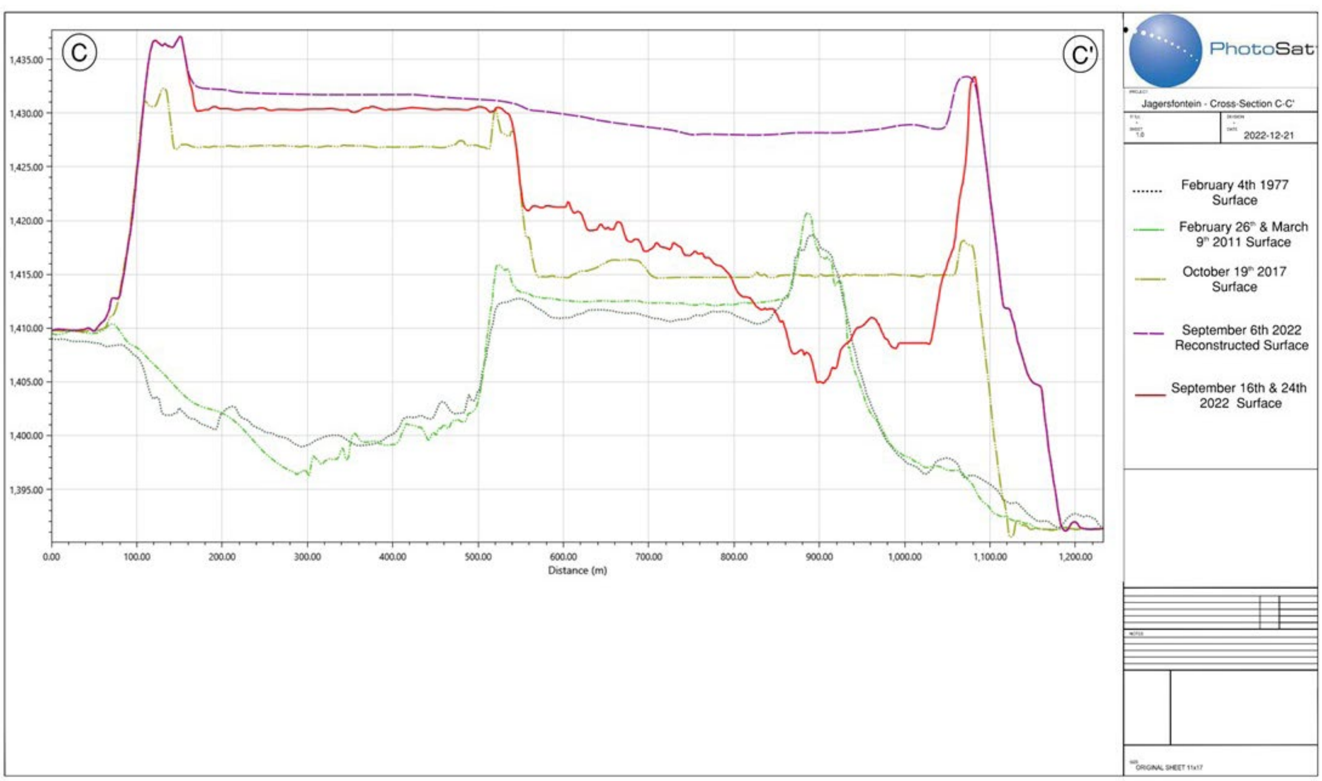


Figure 19: Profiles at cross-section C

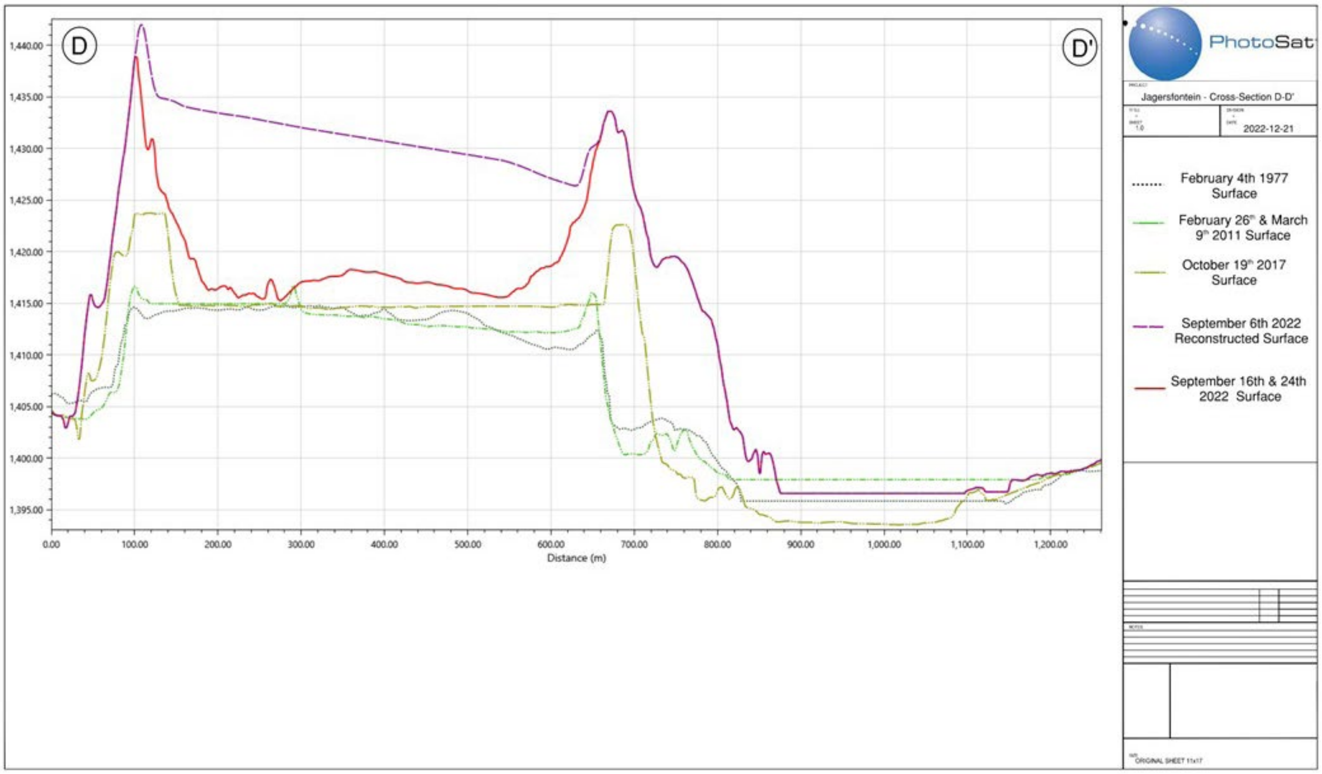


Figure 20: Profiles at cross-section D

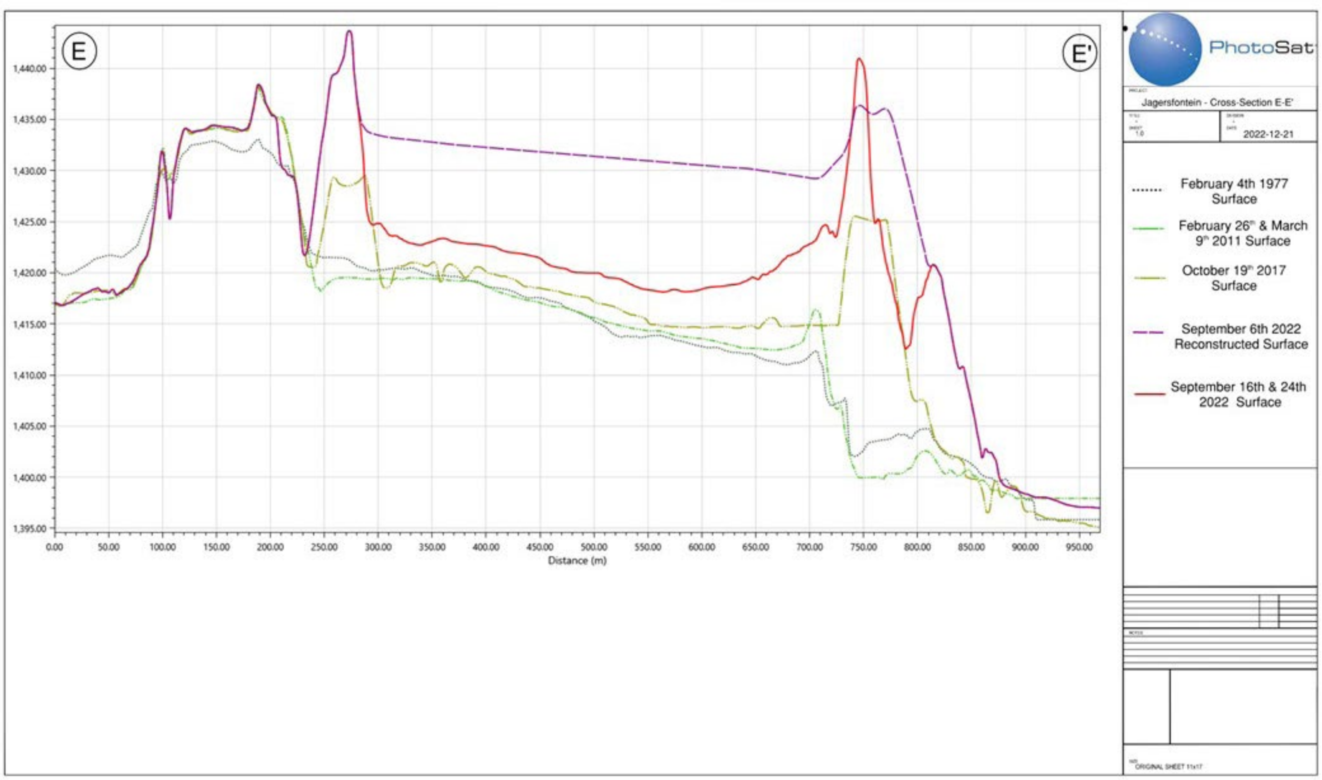


Figure 21: Profiles at cross-section E

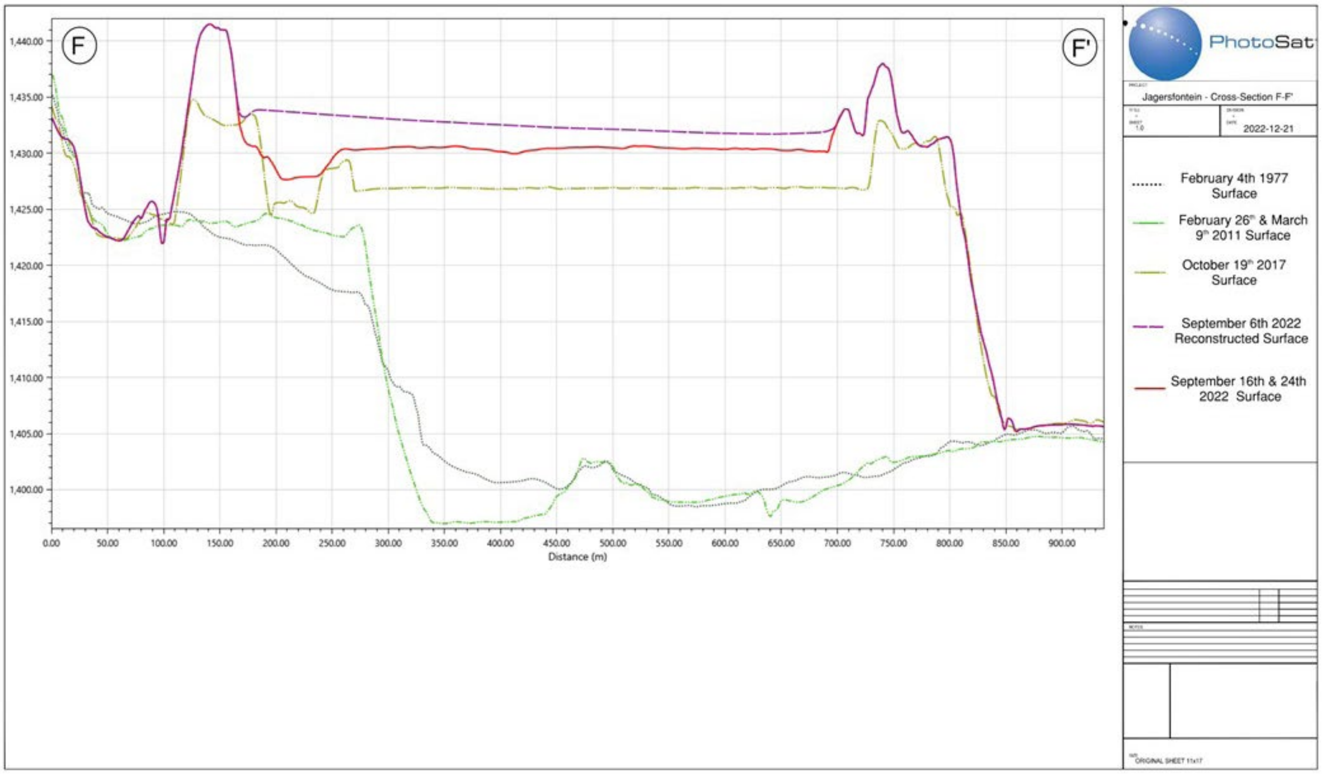


Figure 22: Profiles at cross-section F

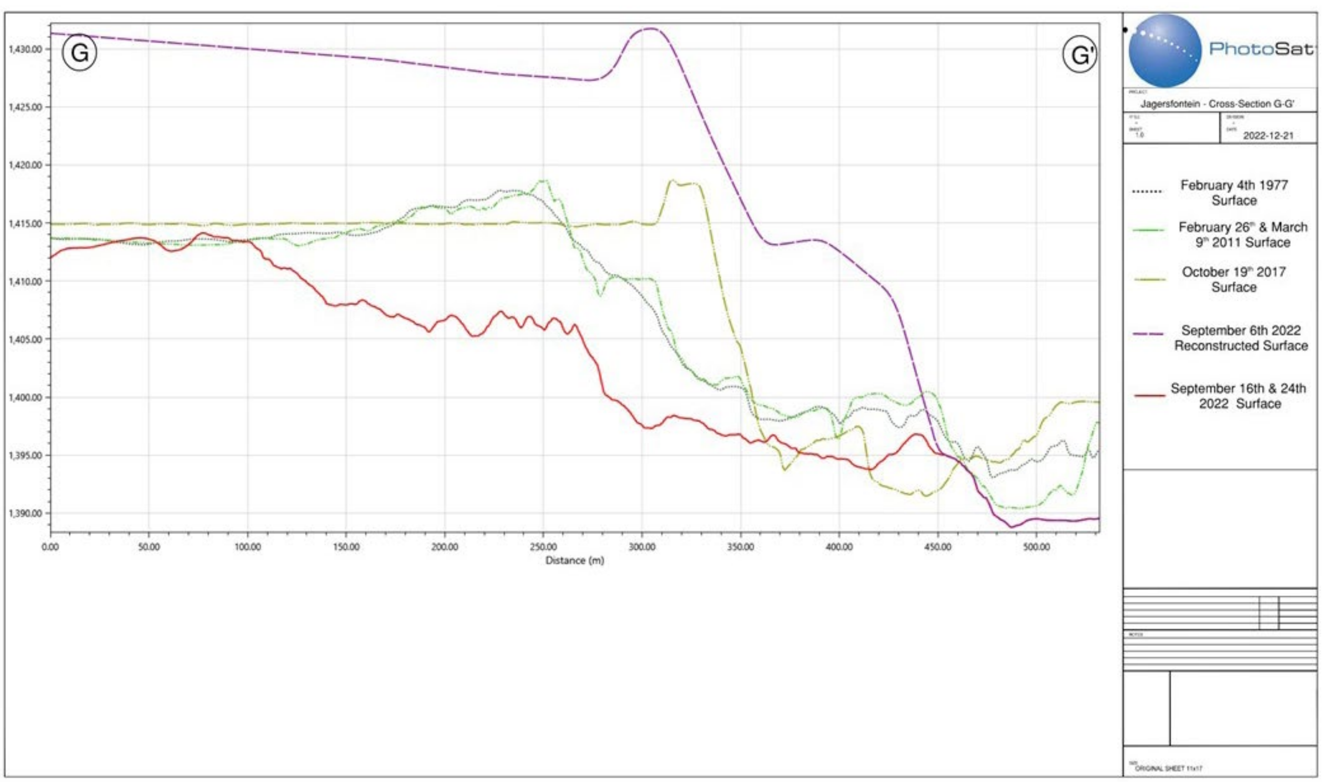


Figure 23: Profiles at cross-section G

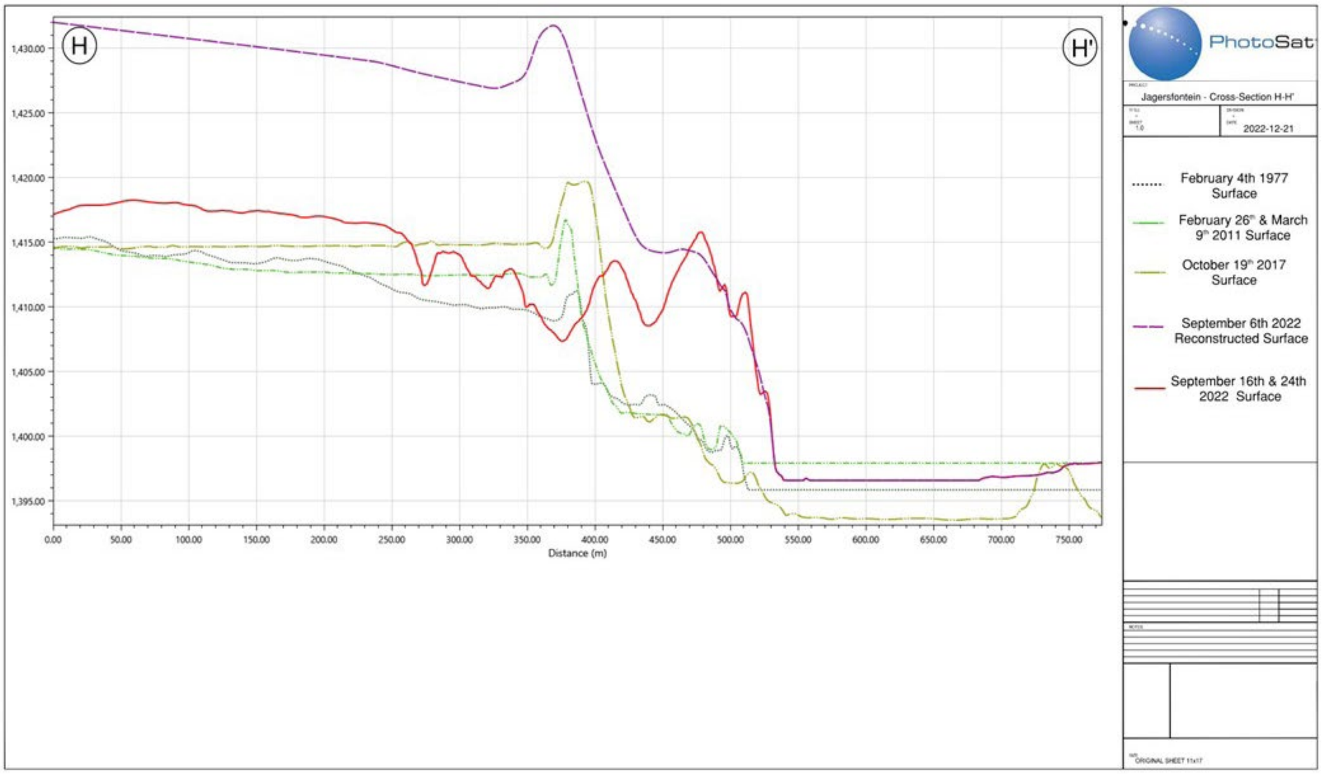


Figure 24: Profiles at cross-section H

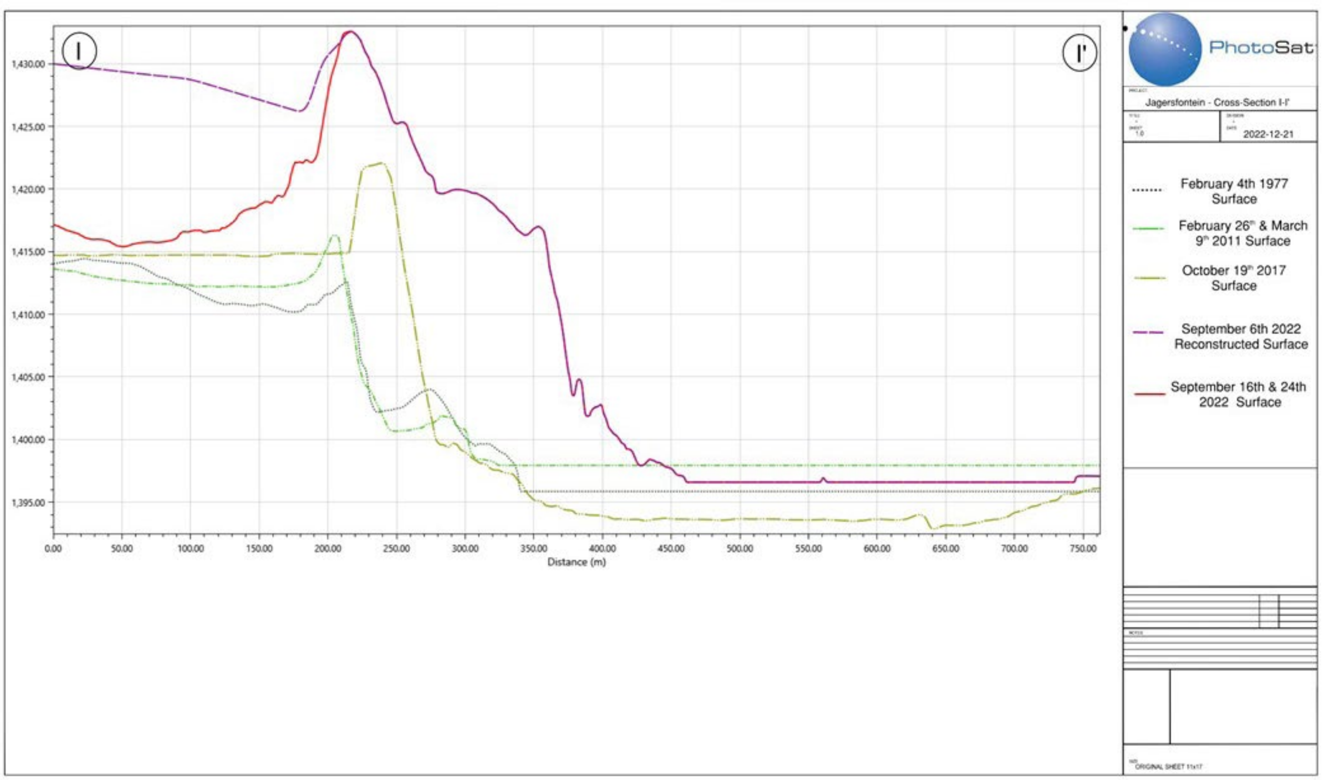


Figure 25: Profiles at cross-section I

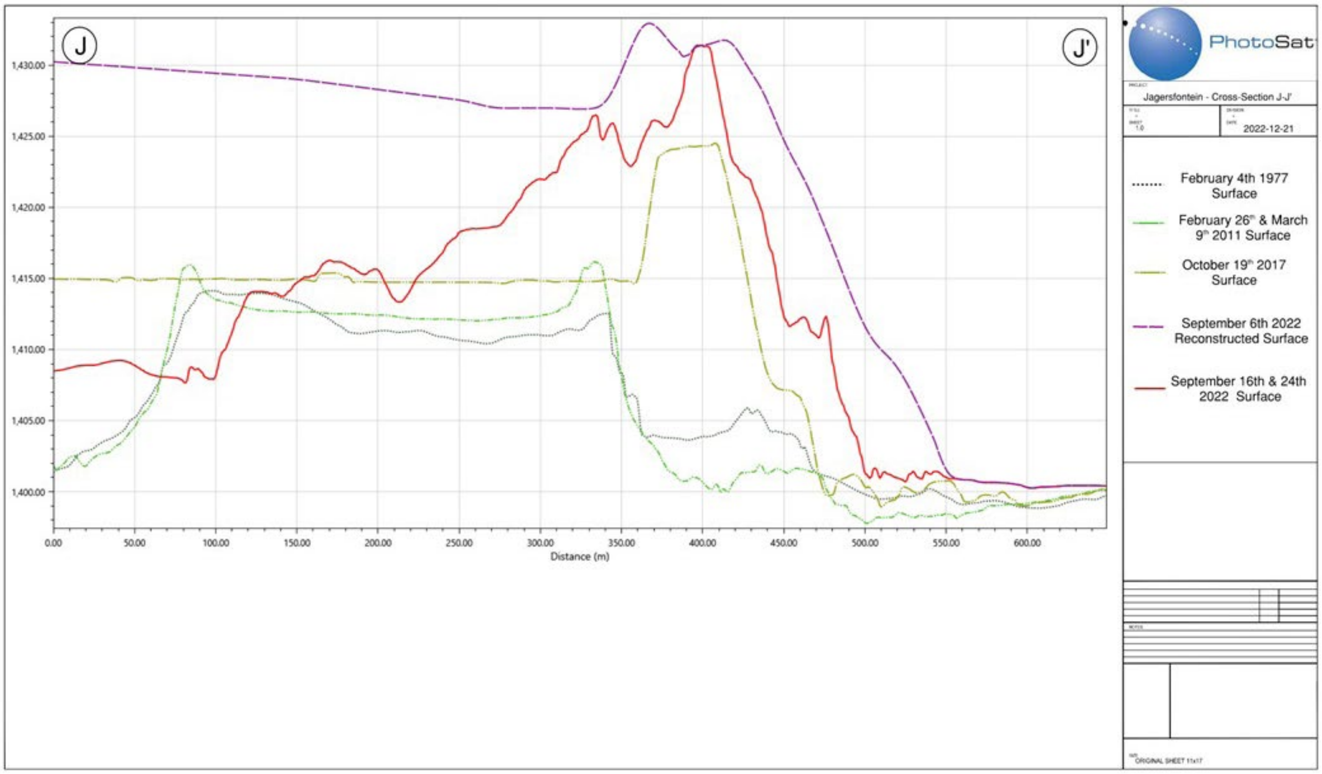


Figure 26: Profiles at cross-section J

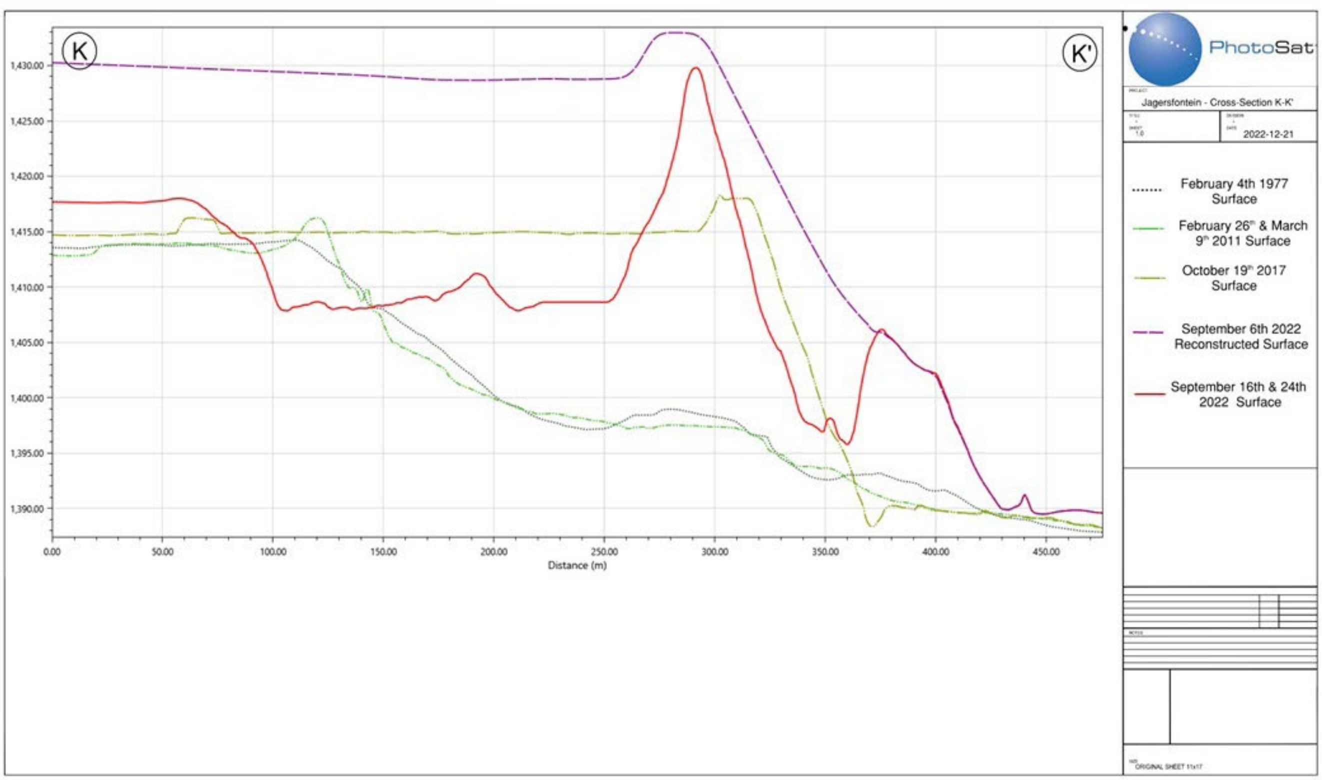


Figure 27: Profiles at cross-section K

Cut/Fill Maps from Successive Surfaces

Heat maps (Fig. 28 to Fig. 31) show the vertical change between the 2011, 2017, 2022 pre-failure, and post-failure surfaces. The total and zone segregated cut and fill volumes can be found in the Table 2 to Table 5. The maps display changes greater than 50 cm. The volumes are accurate to within +/- 10%.

Zone	Area (sq.m)	Fill (cu. m)	Cut (cu.m)	Net (cu.m)
A	132,000	1,641,000	0	1,641,000
B	337,000	7,114,000	2,000	7,112,000
C	37,000	290,000	0	290,000
D	18,000	145,000	0	145,000
E	192,000	236,000	43,000	193,000
Total*	**848,000**	**9,426,000**	**45,000**	**9,381,000**

Table 2: Cut and fill volume from 2011 to 2017 surface

Zone	Area (sq.m)	Fill (cu. m)	Cut (cu.m)	Net (cu.m)
A	229,000	1,284,000	0	1,284,000
B	264,000	3,997,000	0	3,997,000
C	136,000	450,000	28,000	422,000
D	117,000	1,416,000	4,000	1,412,000
E	103,000	1,387,000	0	1,387,000
Total*	**848,000**	**8,534,000**	**32,000**	**8,502,000**

Table 3: Cut and fill volumes from 2017 to 2022 pre-failure surface

Zone	Area (sq.m)	Fill (cu. m)	Cut (cu.m)	Net (cu.m)
A	87,000	981,000	4,000	977,000
B	130,000	1,185,000	76,000	1,109,000
C	101,000	336,000	24,000	312,000
Total*	**848,000**	**4,116,000**	**656,000**	**3,460,000**

Table 4: Cut and fill volumes from 2017 to 2022 post-failure surface

Zone	Area (sq.m)	Fill (cu. m)	Cut (cu.m)	Net (cu.m)
Embankment Structure	80,000	10,000	660,000	-650,000
Tailings	475,000	-	4,390,000	-4,390,000
TOTAL	**555,000**	**10,000**	**5,050,000**	**-5,040,000**

Table 5: Cut and fill volumes from 2022 pre-failure to post-failure surface

**The total volumes row corresponds to the material movement within the entire 2022 Dyke footprint and it is not the sum of the zone rows above.*

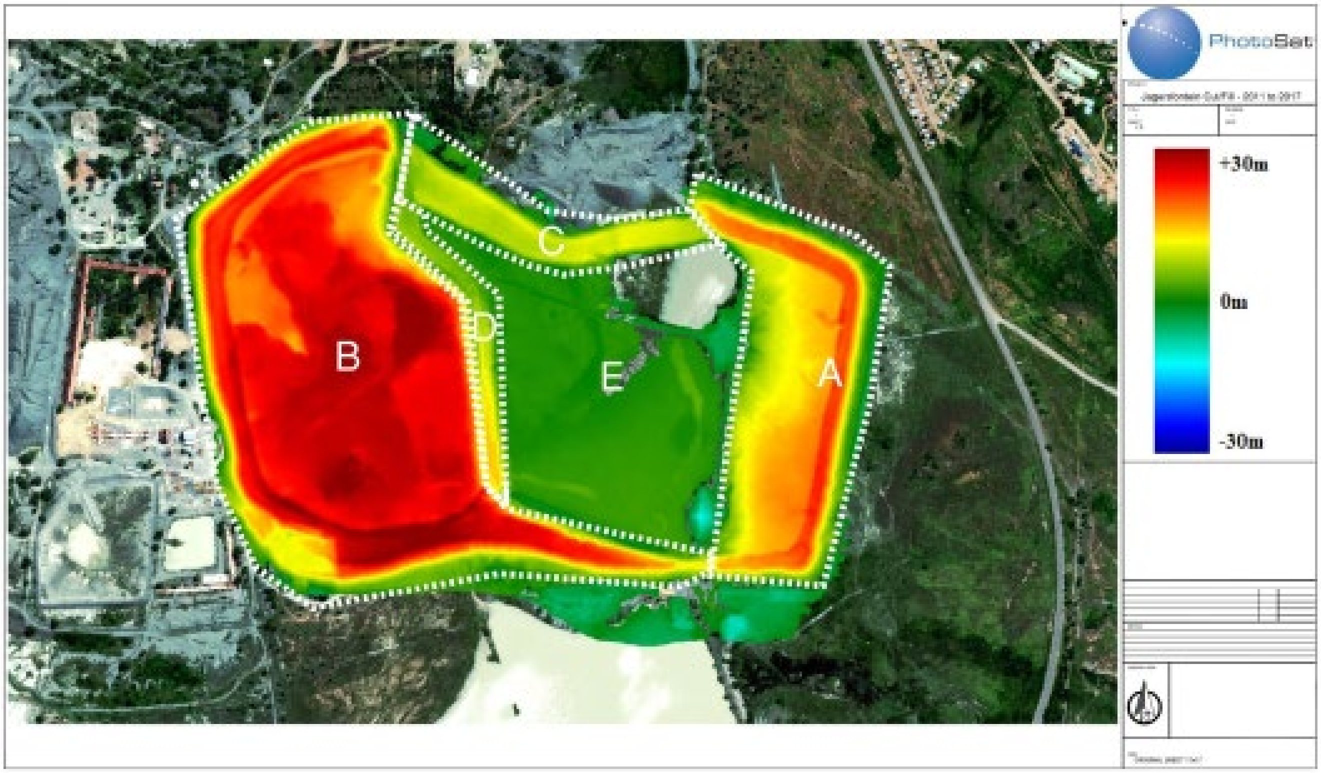


Figure 28: Cut and fill map from 2011 to 2017 surface

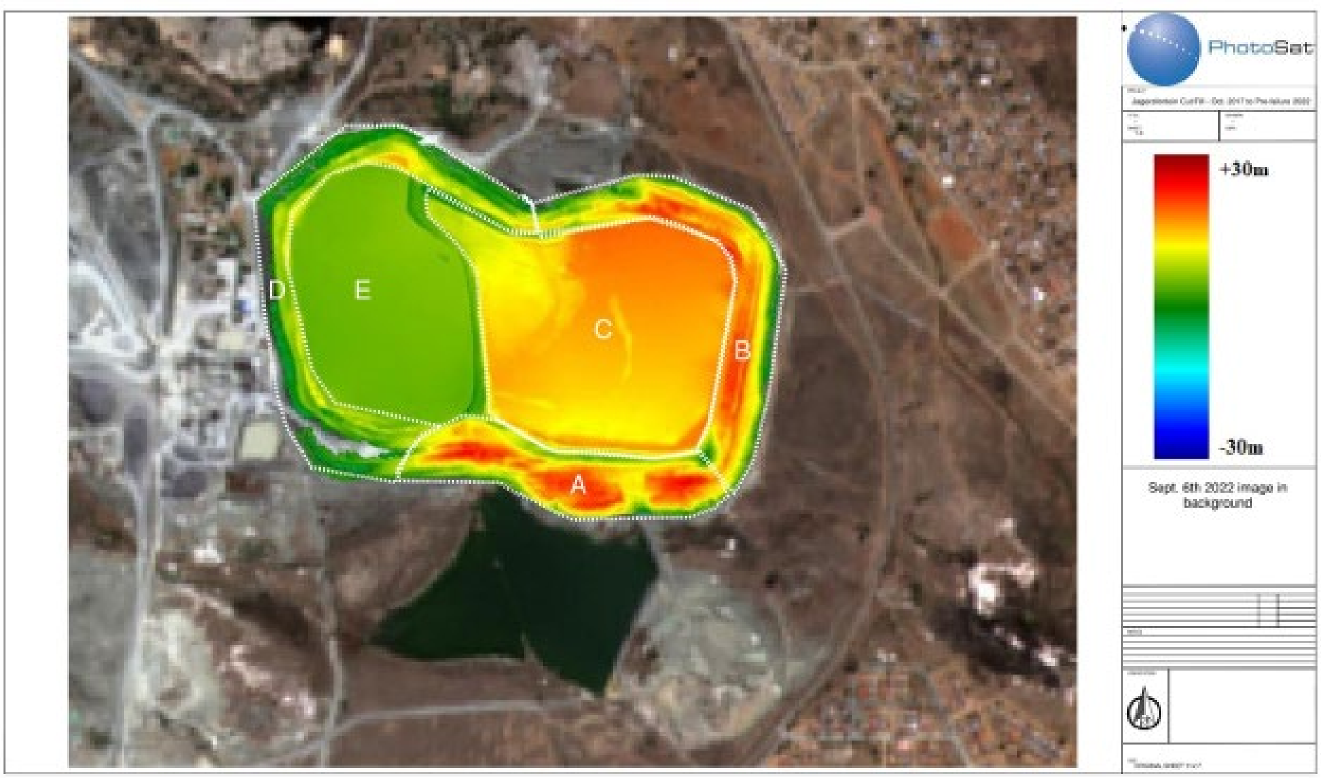


Figure 29: Cut and fill map from 2017 to 2022 pre-failure surface

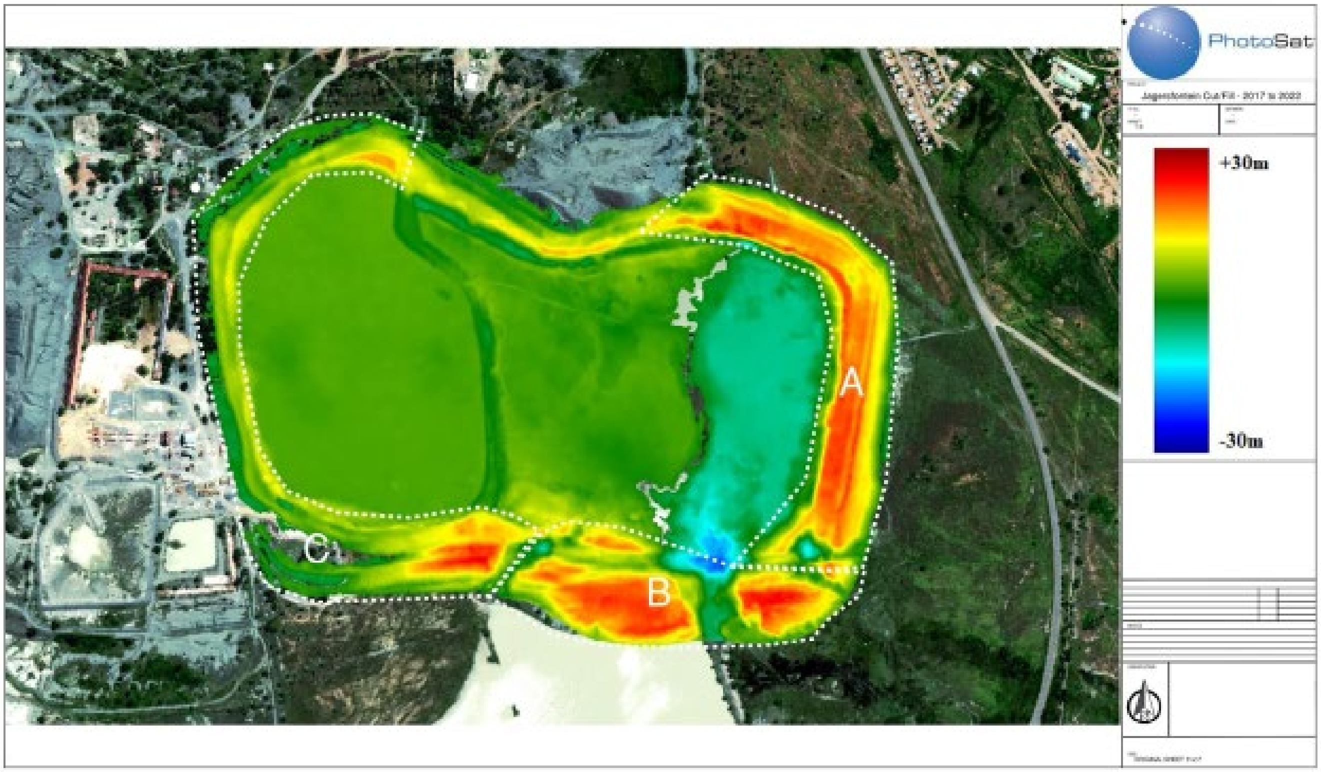


Figure 30: Cut and fill map from 2017 to 2022 post-failure surface

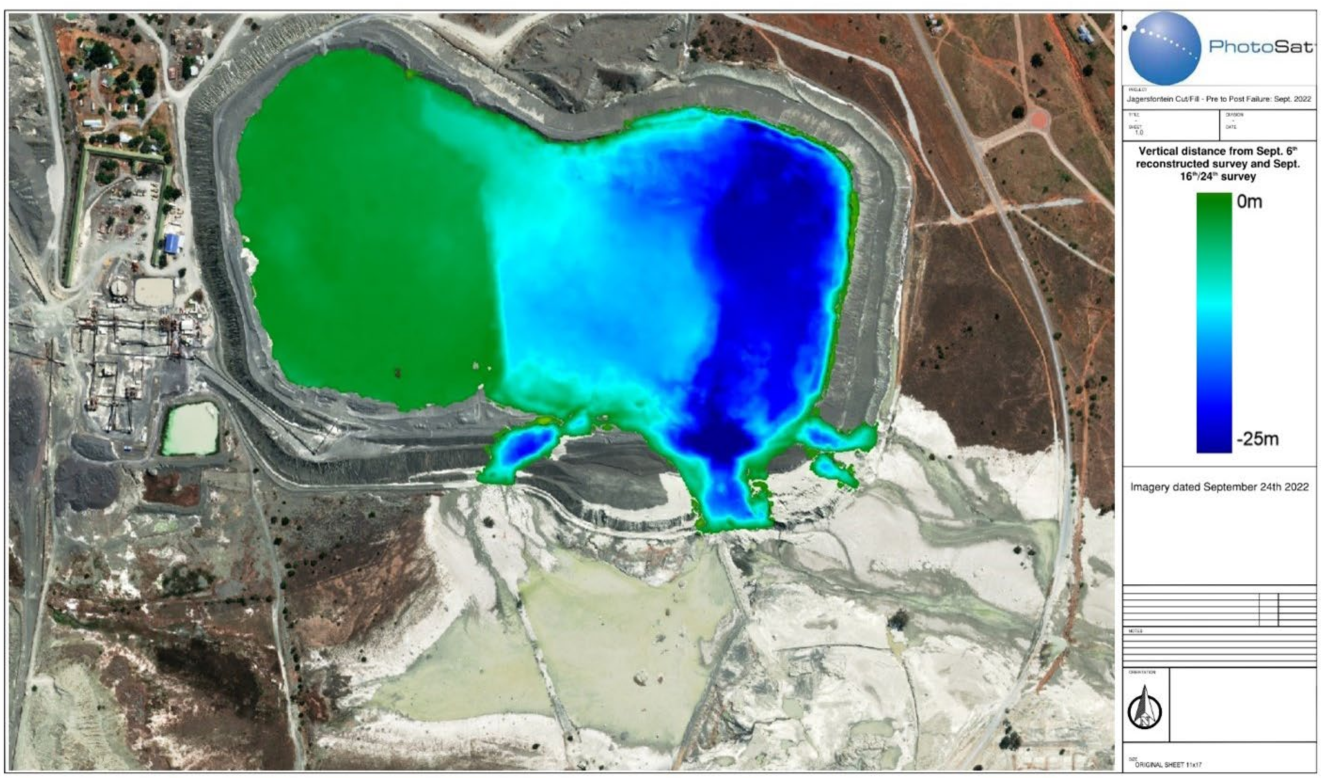


Figure 31: Cut and fill map from 2022 pre-failure to post-failure surface

TSF Environmental Containment Freeboard

The vertical distance between the pond or tailings elevation and the elevation of the lowest point of the dyke wall is the environmental containment freeboard. (Fig. 32)

The maps below (Fig. 33 to Fig. 35) display the distance by color, where warmer the color corresponds to greater freeboard distance.

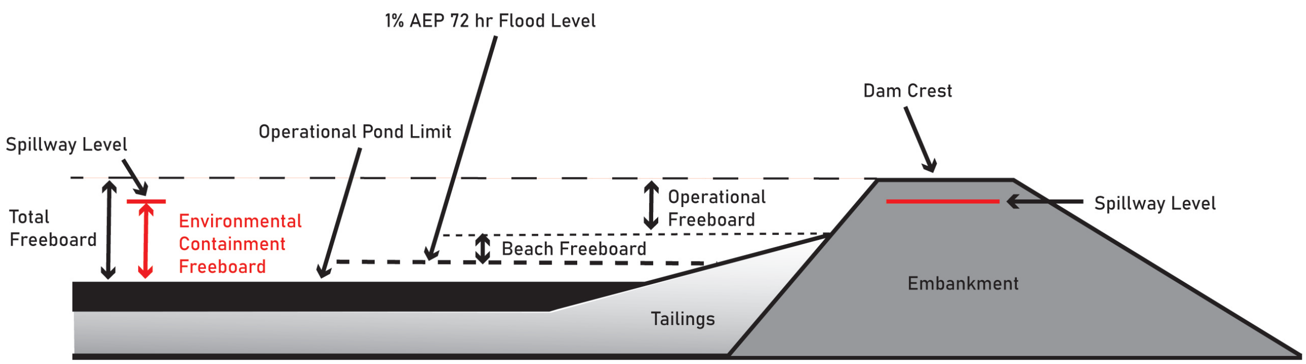


Figure 32: Diagram of environmental containment freeboard

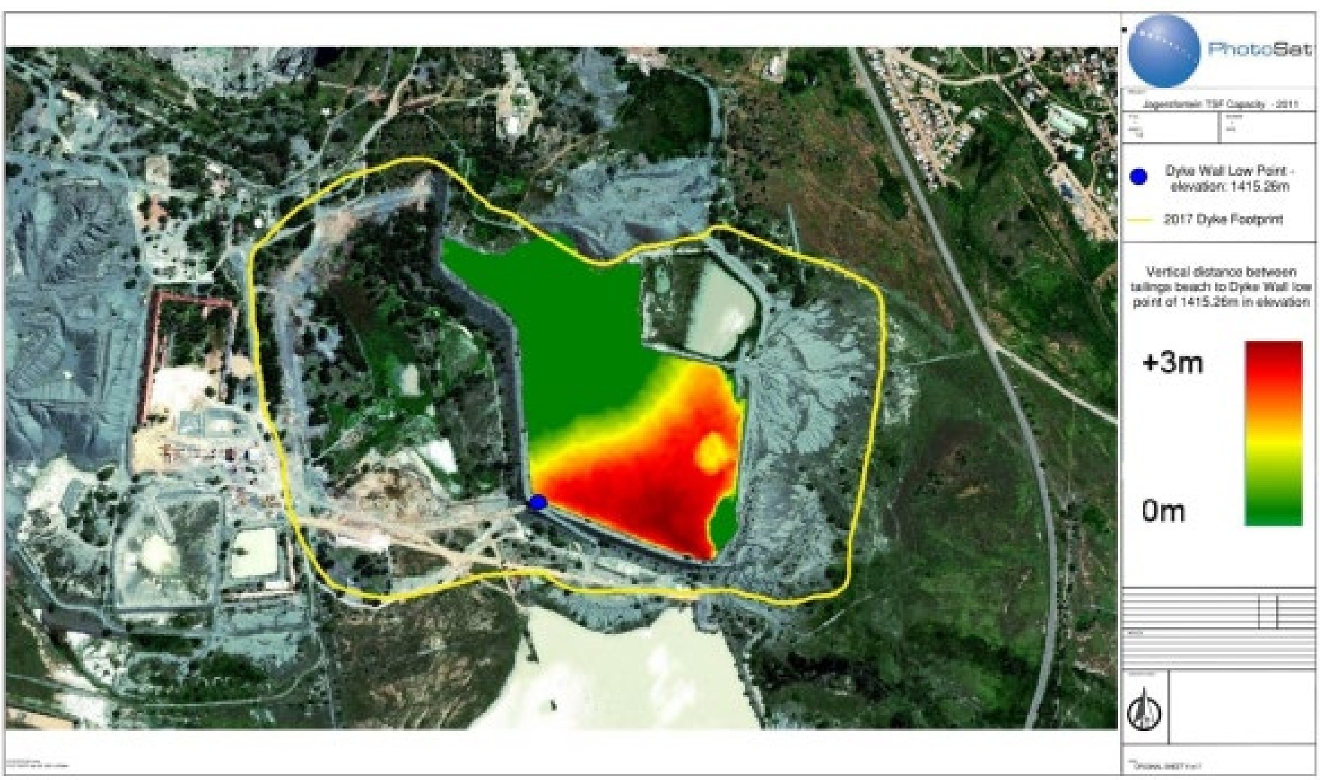


Figure 33: TSF environmental containment freeboard map for 2011

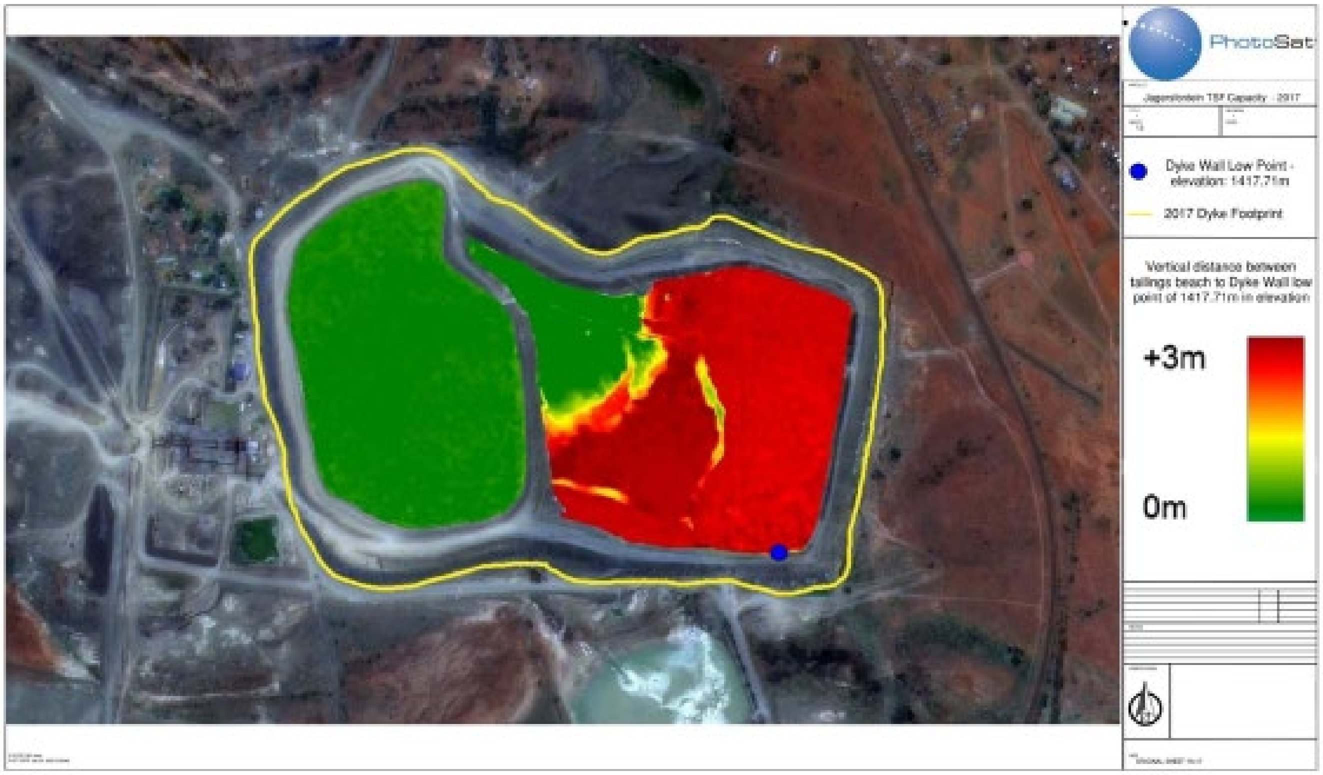


Figure 34: TSF environmental containment freeboard map for 2017

Figure 35: TSF environmental containment freeboard map for 2022

Spillway

There is a spillway visible in the dividing wall, shown below in Figure 36.

Figure 36: Spillway in dividing wall from October 19th 2017

TSF Operational Freeboard

The vertical distance between the point where tailings contact the dyke wall and the upstream shoulder of the dyke wall at that location is the operational freeboard. (Fig. 37) The maps below (Fig. 38 to Fig. 40) display the distance by color, where warmer the color corresponds to greater freeboard distance. In some areas of the TSF, the wall was not visible. In those areas, freeboard was not measured.

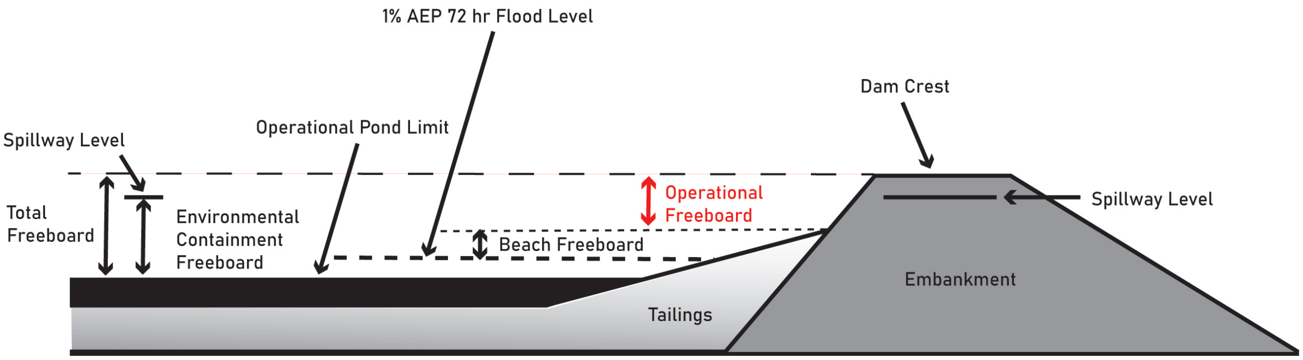


Figure 37: Diagram of operational freeboard

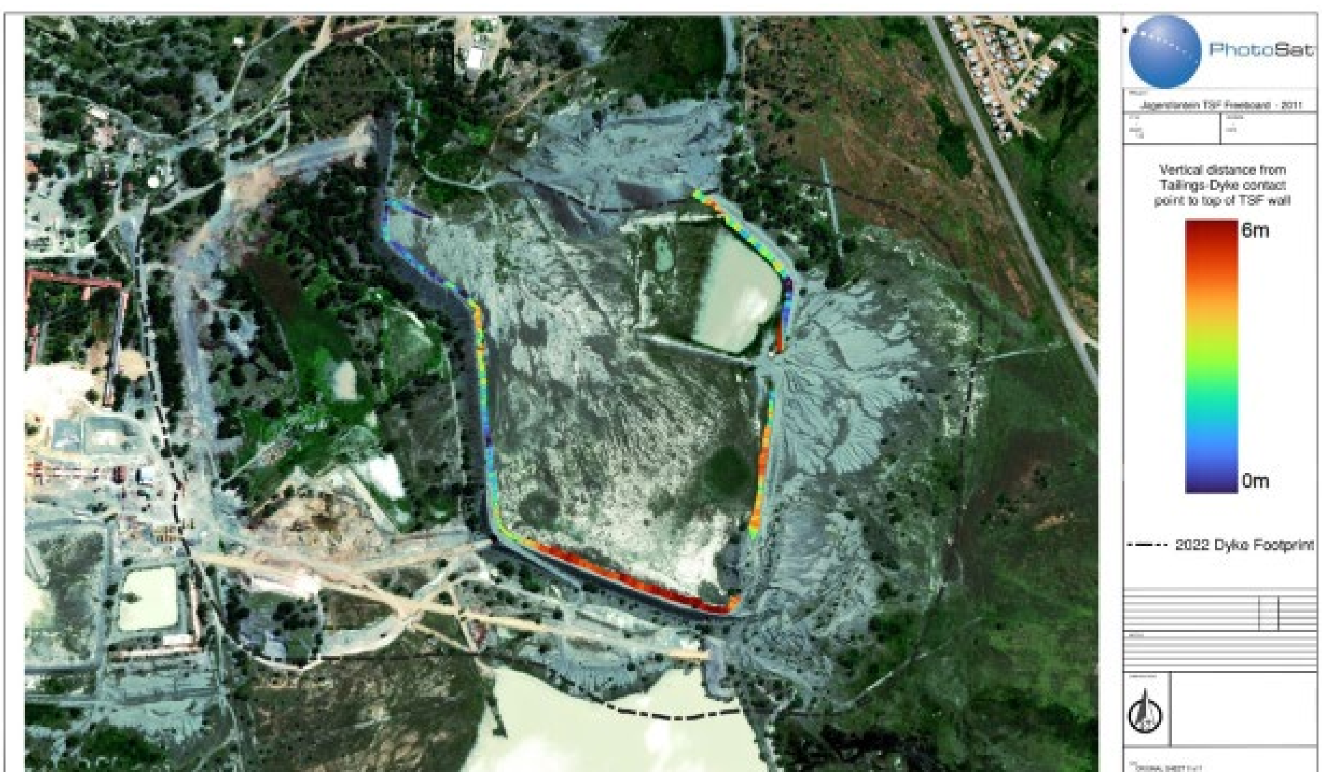


Figure 38: TSF operational freeboard map for 2011

Figure 39: TSF operational freeboard map for 2017

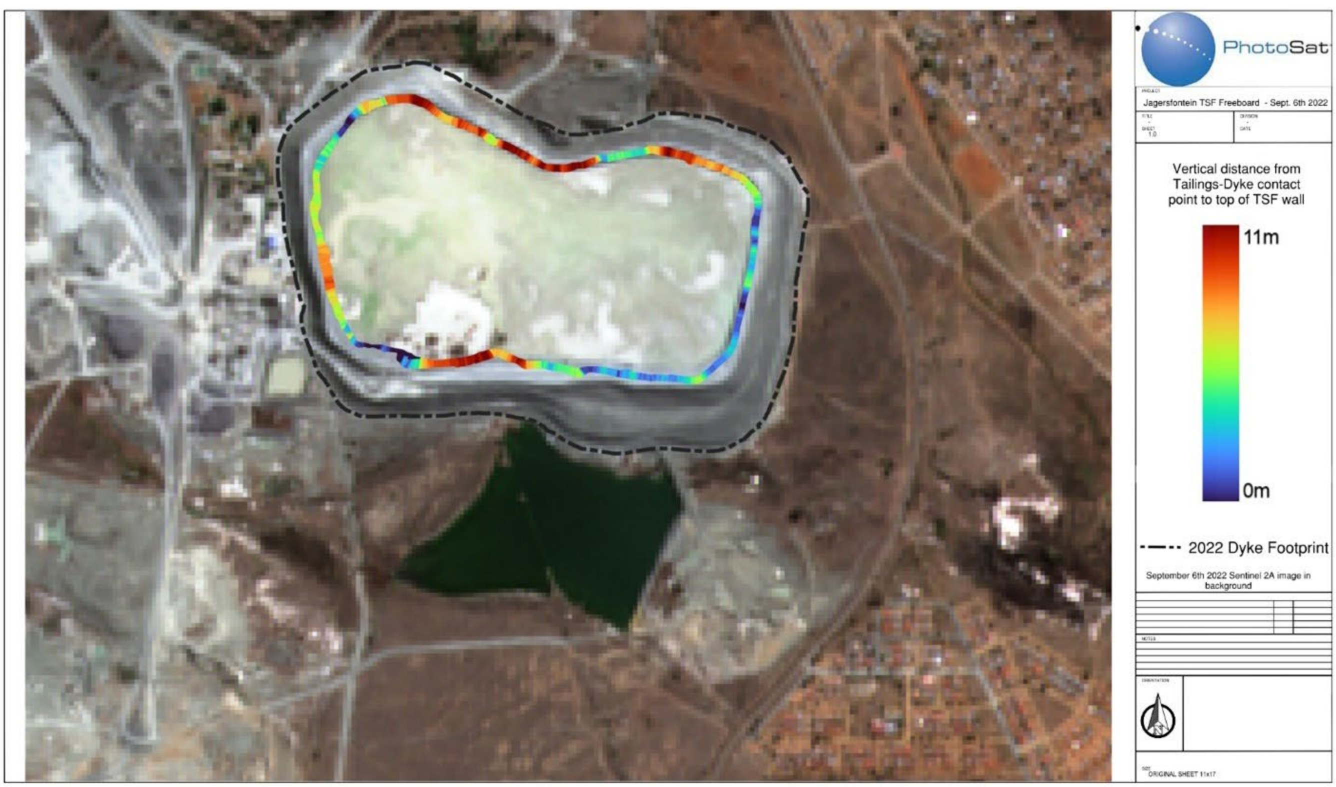


Figure 40: TSF operational freeboard map for 2022

TSF Dyke Wall Height

The dyke wall height (Fig. 41) along the upstream crest was measured for 2011 and 2017 using topographic surfaces. The dyke wall height was measured for 2022 using the reconstructed surface.

Shown below (Fig. 42 to Fig. 44) is the range in the wall height along the entire TSF, with warmer colors indicating higher elevations.

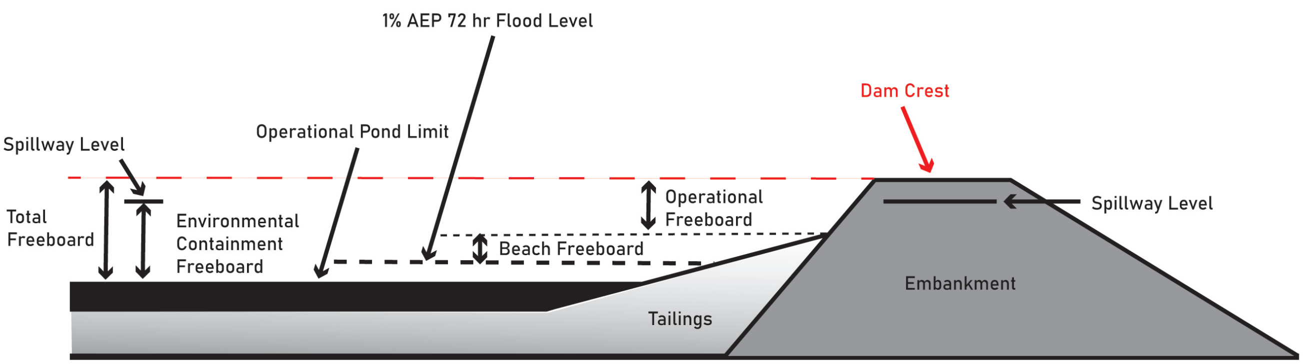


Figure 41: Diagram of dam crest

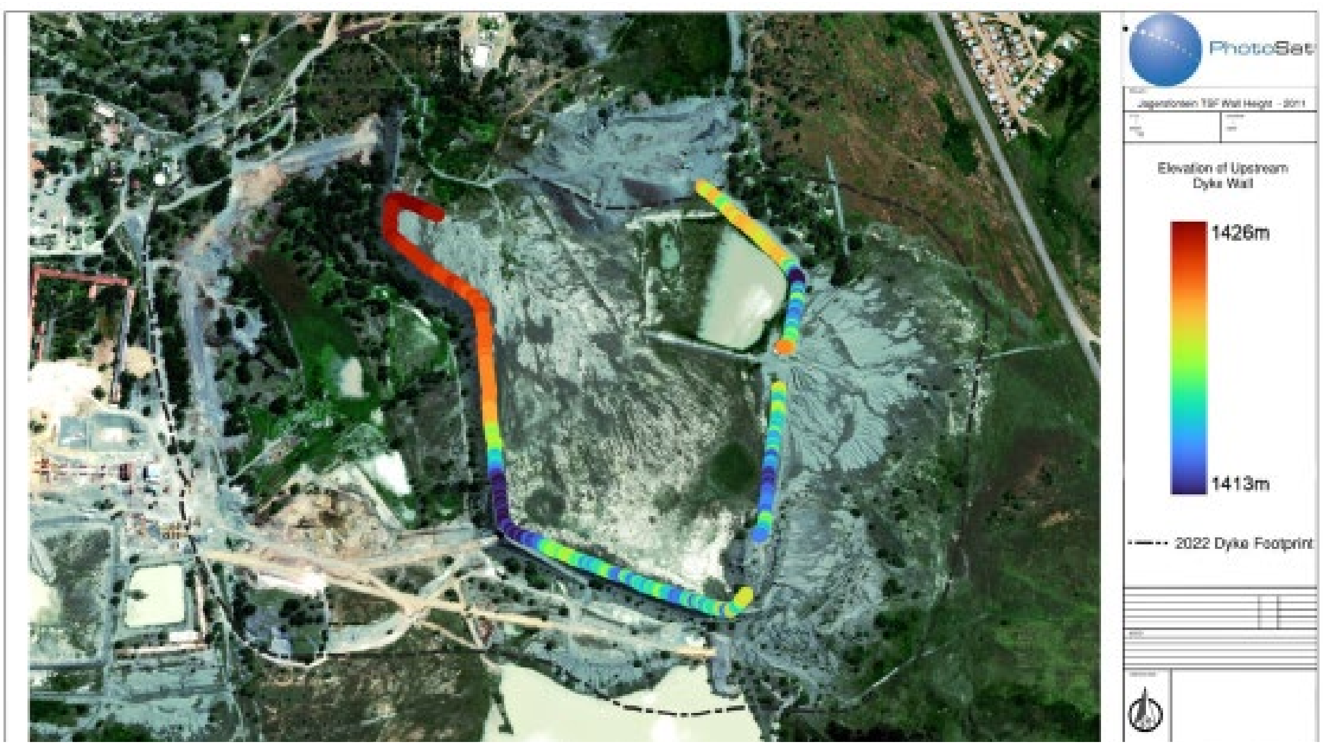


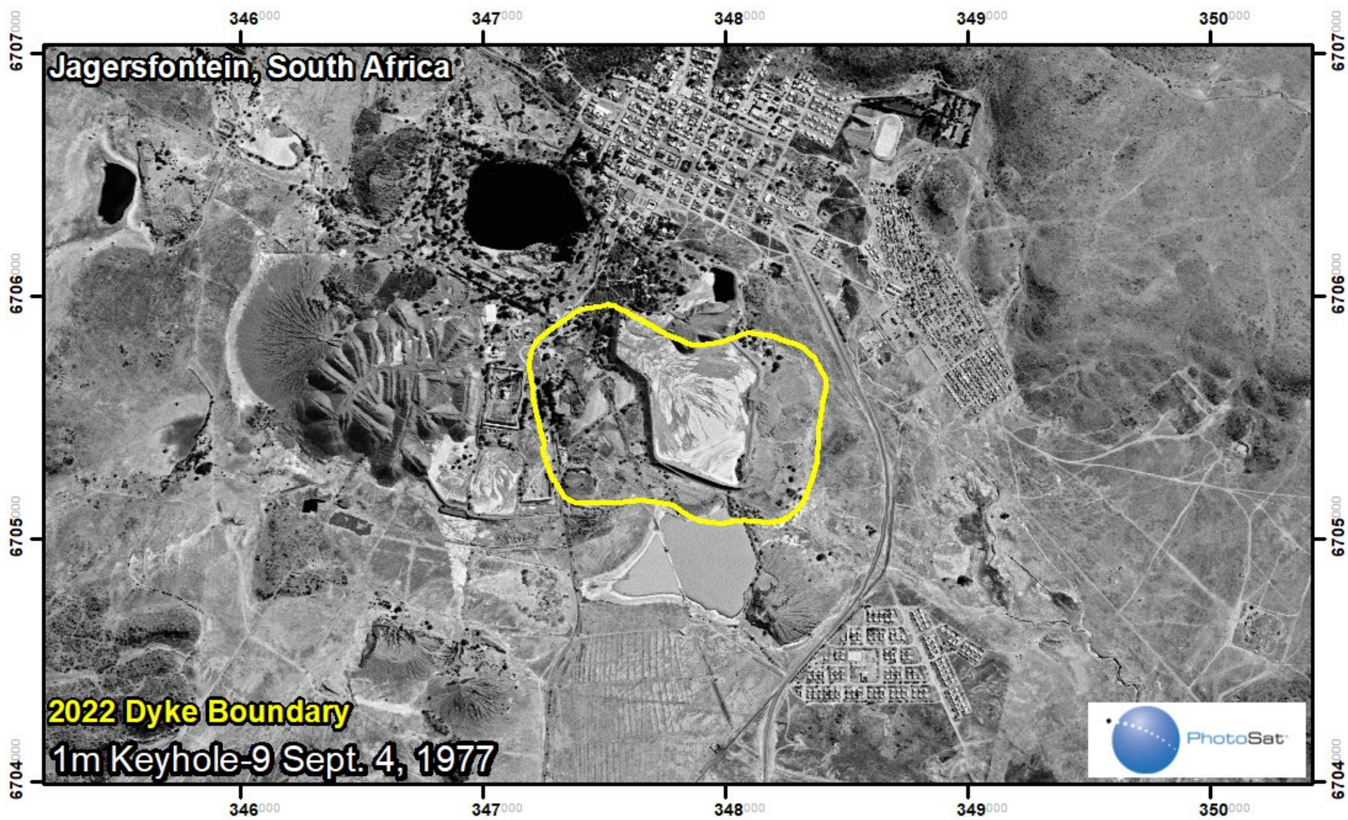
Figure 42: TSF upstream wall height for 2011

Figure 43: TSF upstream wall height for 2017

Figure 44: TSF upstream wall height for 2022

Appendix A

The following pages show the satellite images in chronological order that were found in the archive search.


Jagersfontein, South Africa
2022 Dyke Boundary
1m Keyhole-9 Sept. 4, 1977
PhotoSat
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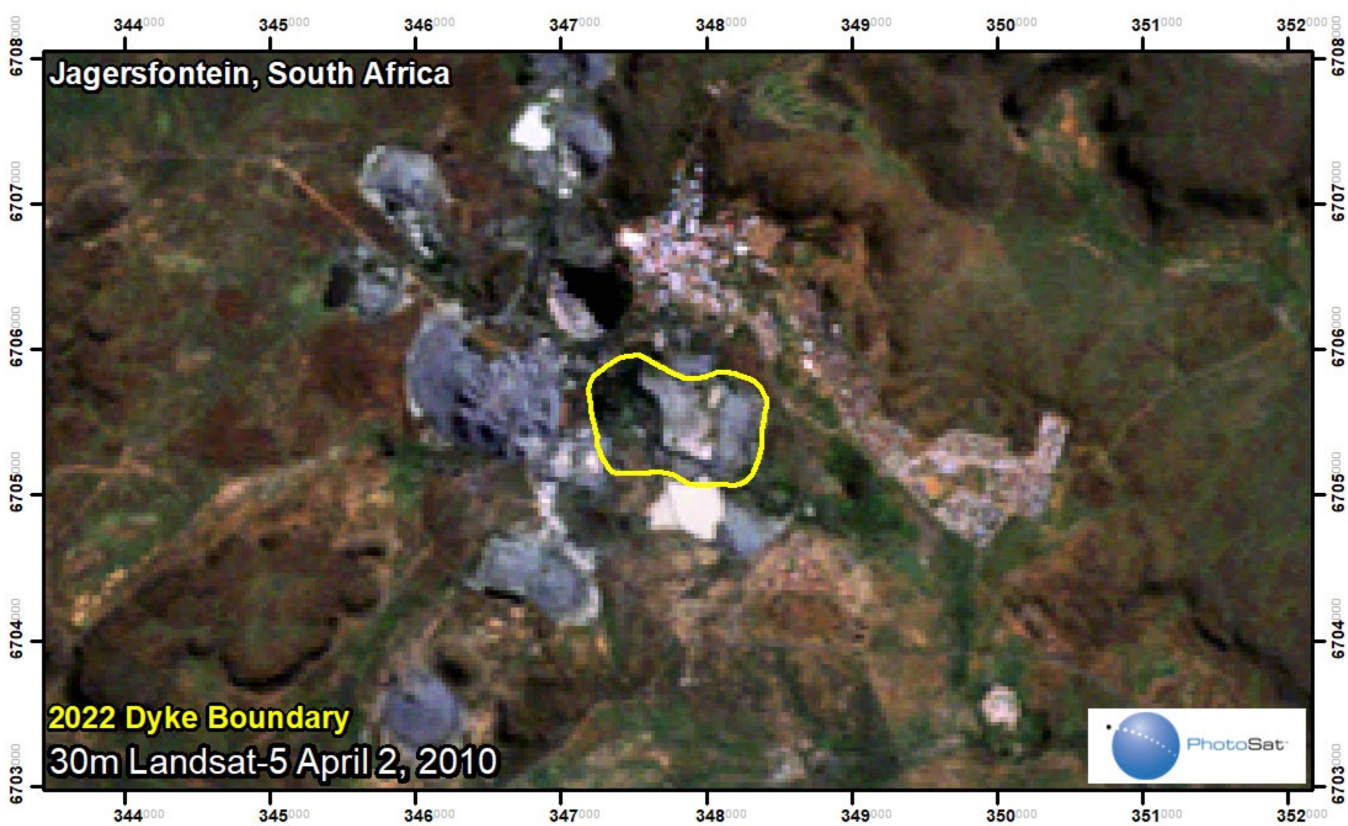
Jagersfontein, South Africa
2022 Dyke Boundary
30m Landsat-5 April 2, 2010
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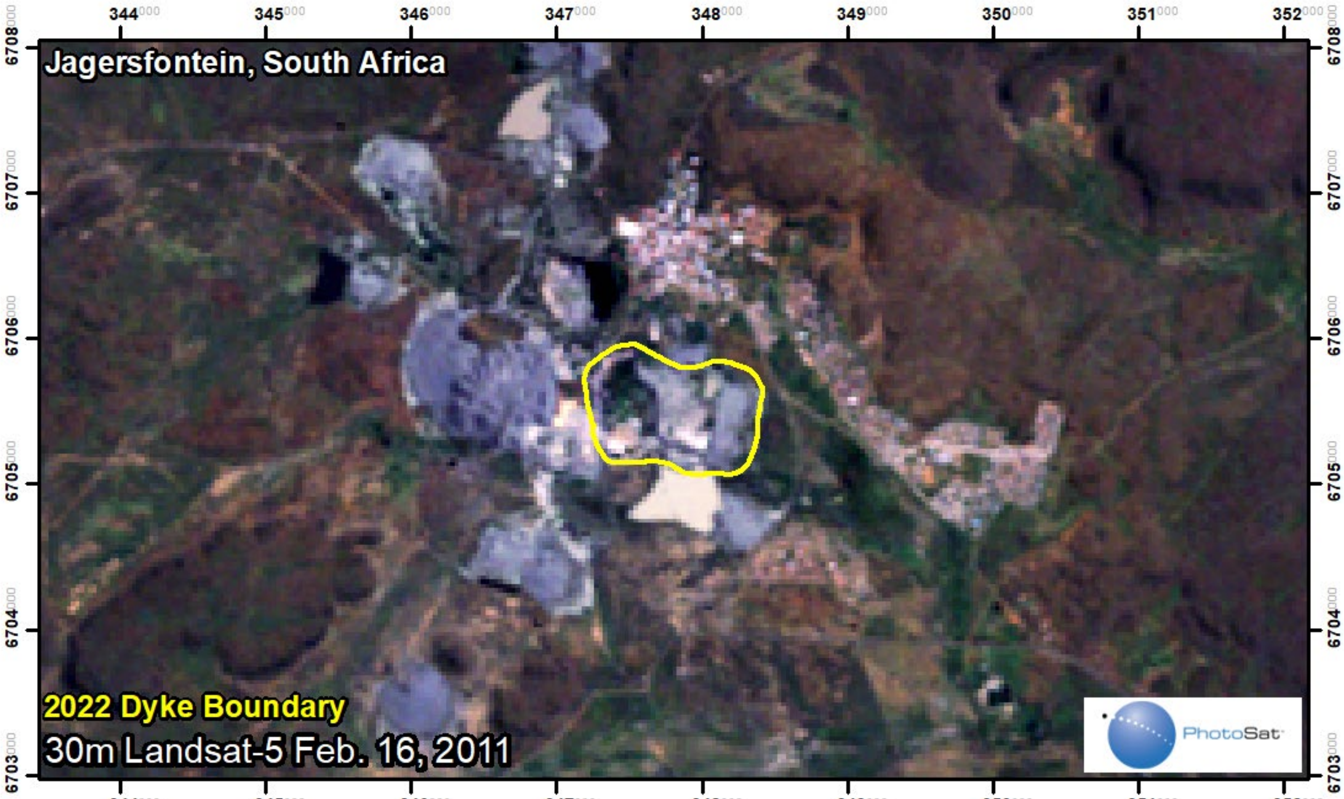
Jagersfontein, South Africa
2022 Dyke Boundary
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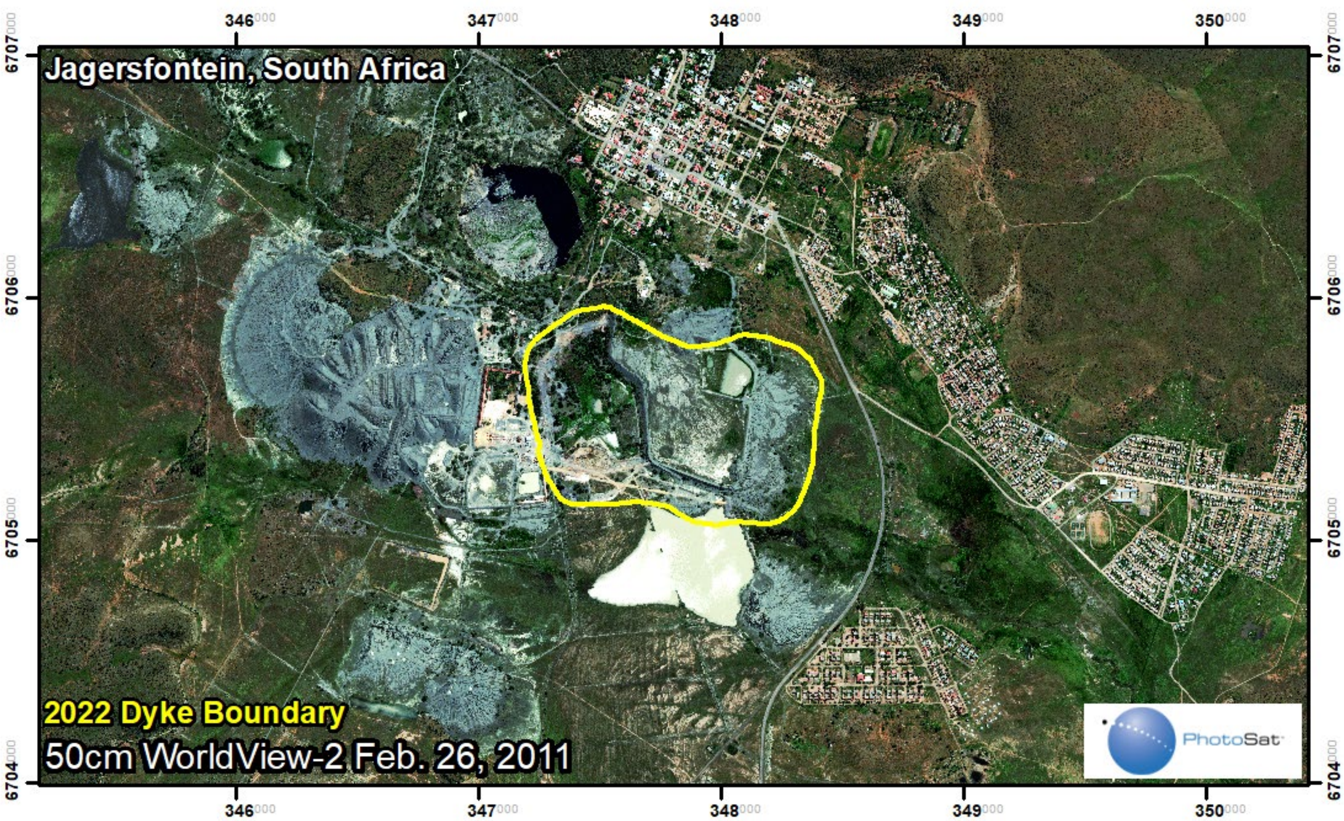
Jagersfontein, South Africa
2022 Dyke Boundary
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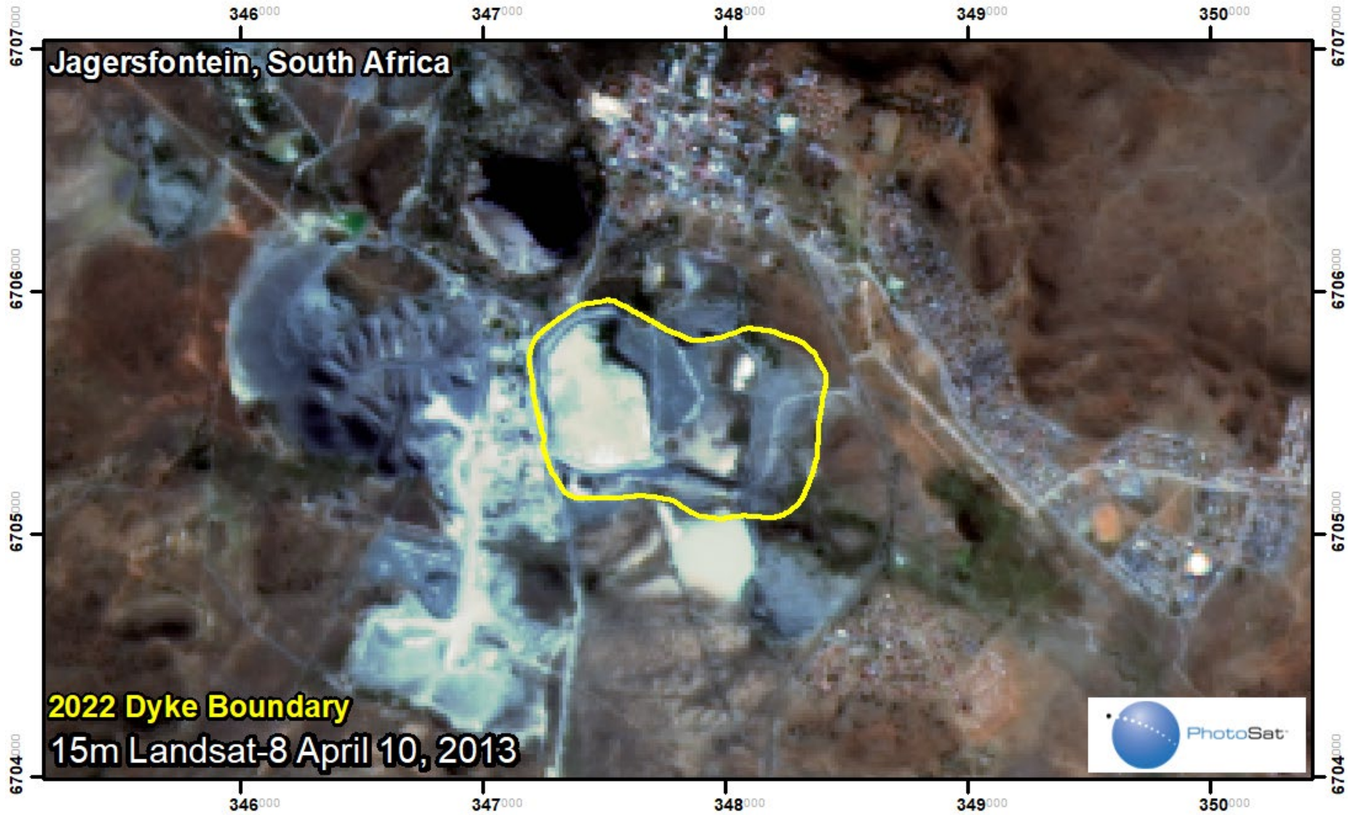
Jagersfontein, South Africa
2022 Dyke Boundary
15m Landsat-8 April 10, 2013
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
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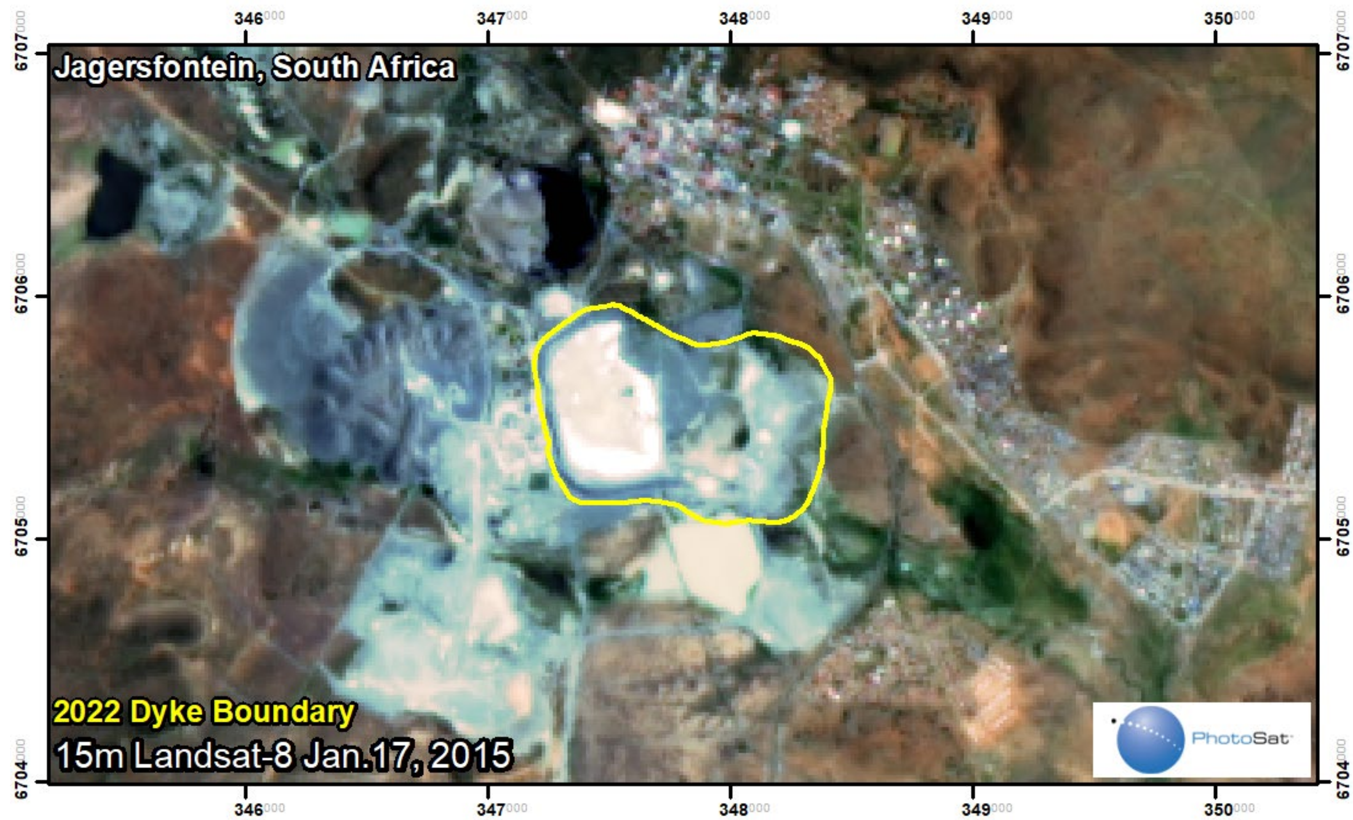
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Jagersfontein, South Africa
2022 Dyke Boundary
15m Landsat-8 Jan.17, 2015
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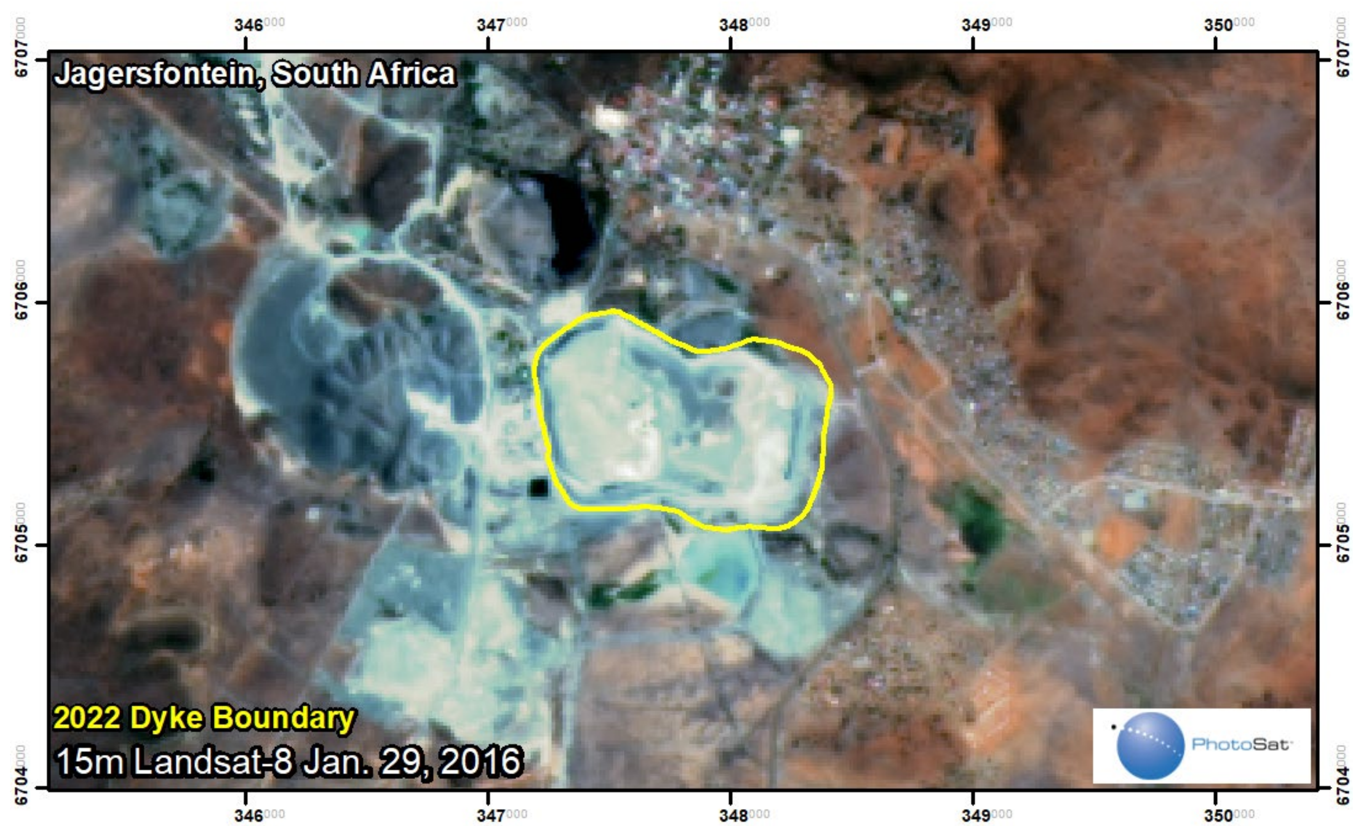
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Jagersfontein, South Africa
2022 Dyke Boundary
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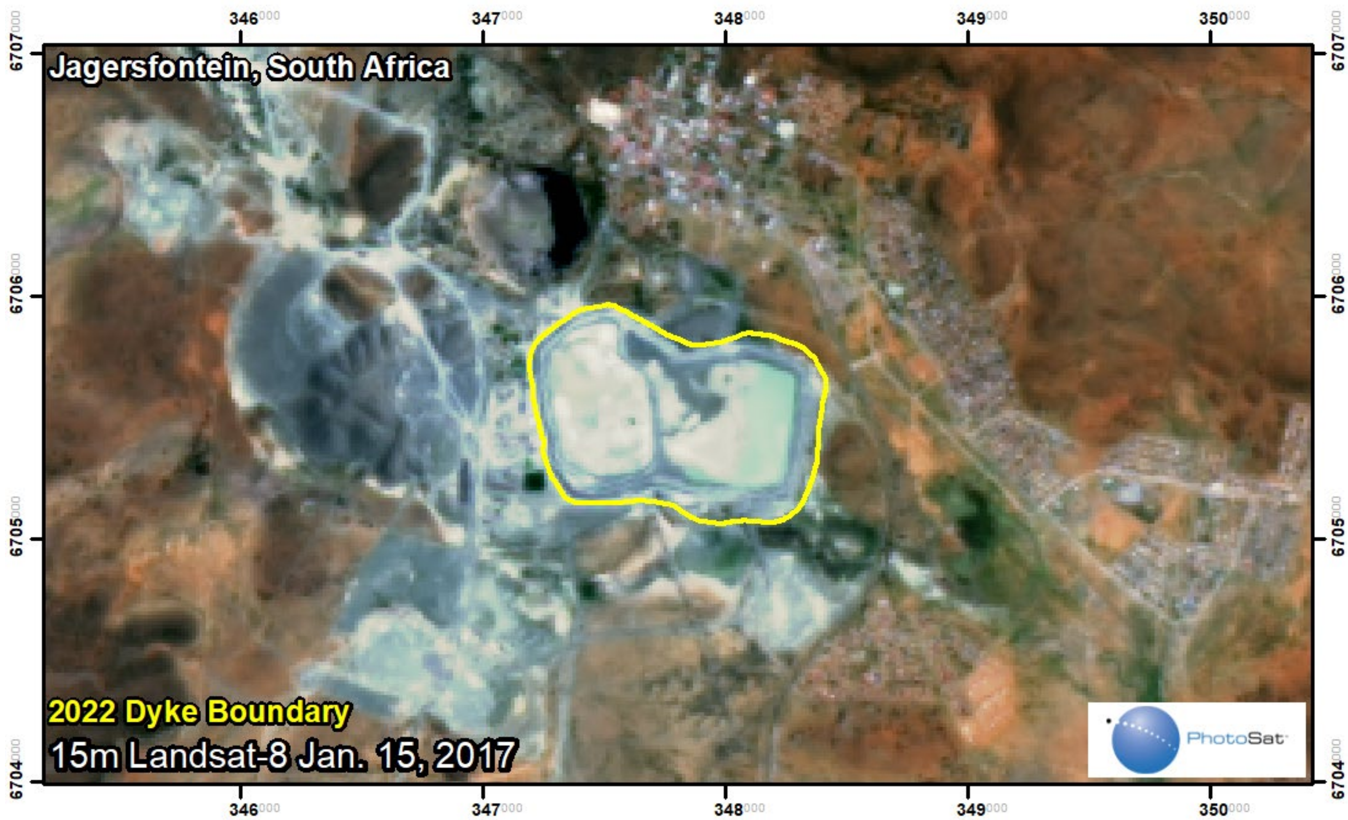
PhotoSat


Jagersfontein, South Africa
2022 Dyke Boundary
15m Landsat-8 Jan. 15, 2017
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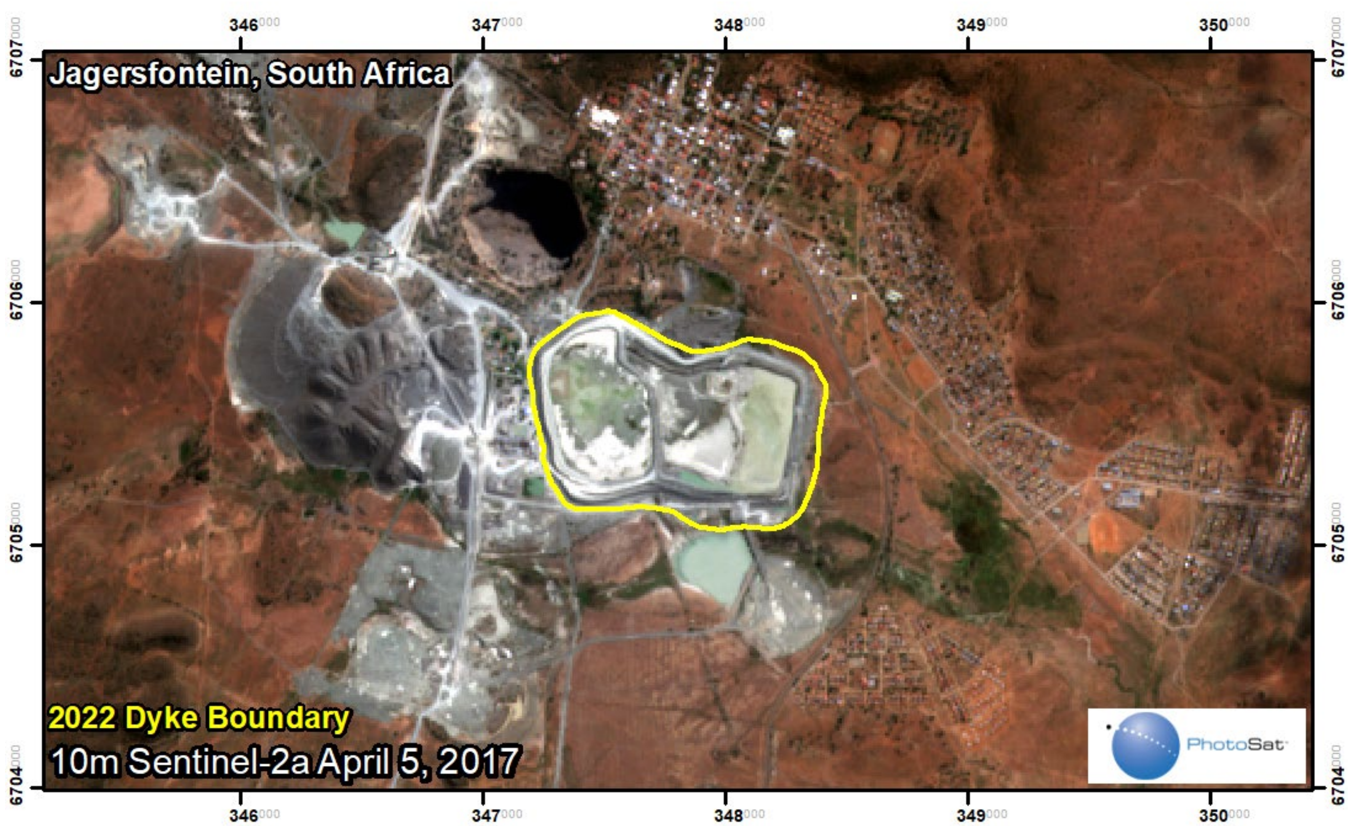
Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a April 5, 2017
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
50cm WorldView-1 Oct. 19, 2017 (10m Sentinel-2a April 5, 2017)
PhotoSat
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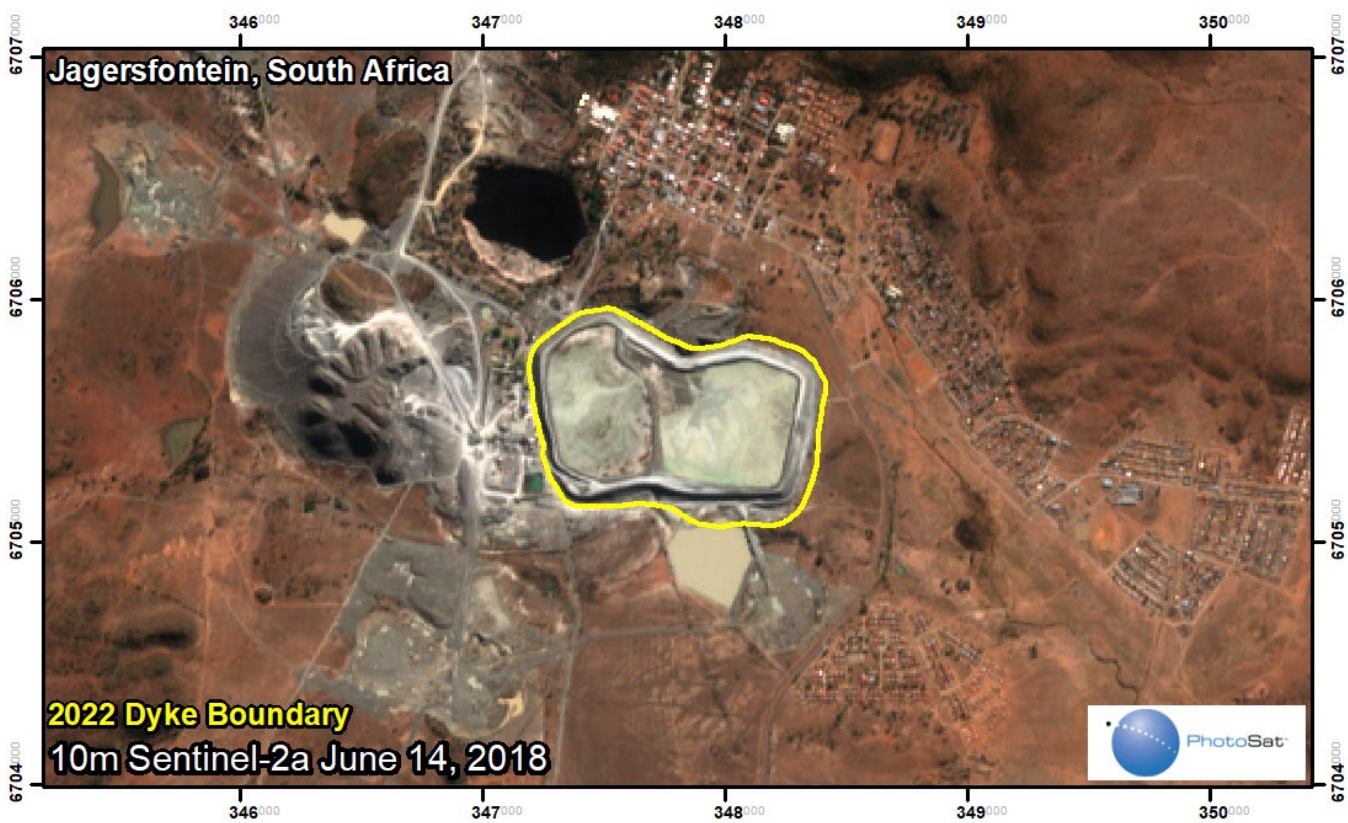
Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a June 14, 2018
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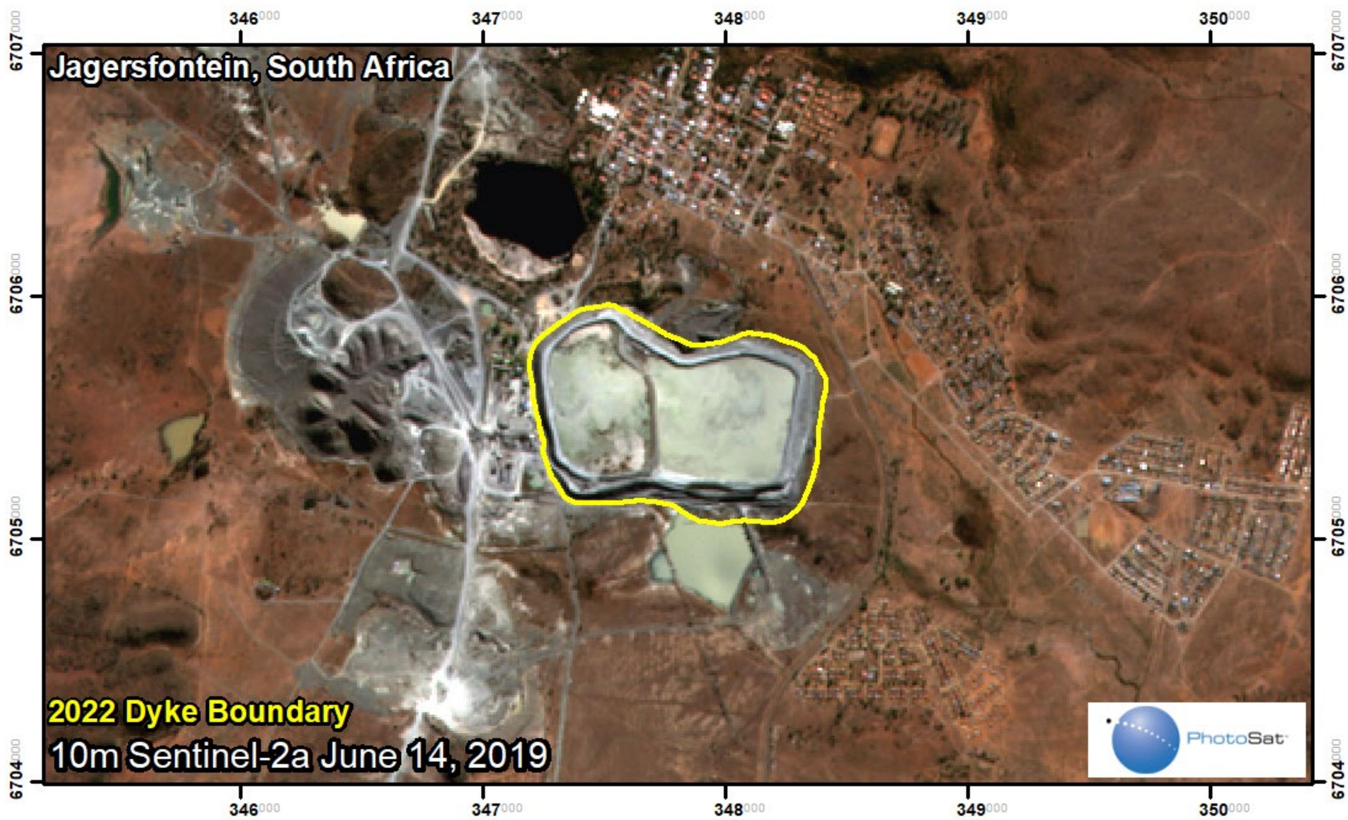
Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a June 14, 2019
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a June 18, 2020
PhotoSat
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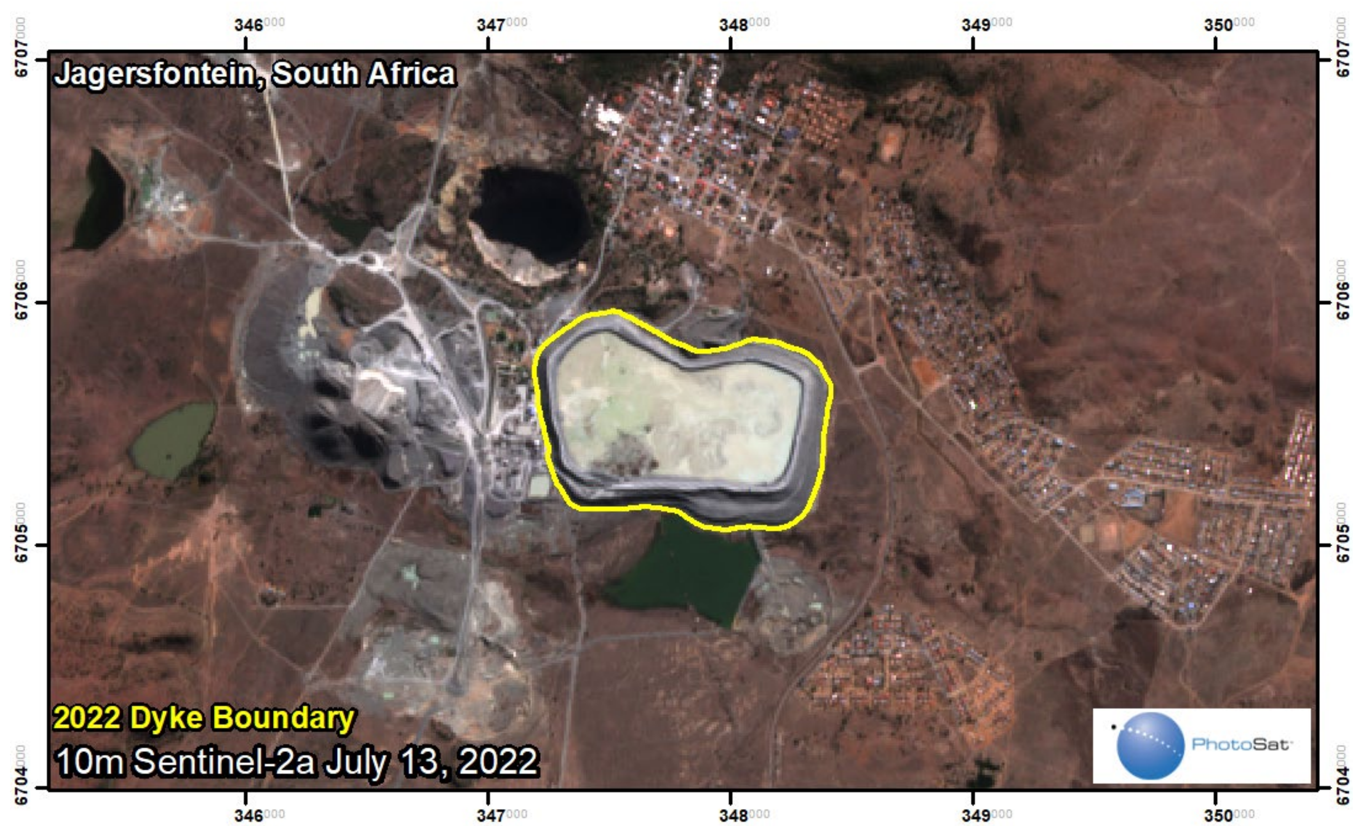
Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a June 18, 2021
PhotoSat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Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a July 13, 2022
PhotoSat


Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a Aug. 2, 2022
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a Aug. 17, 2022
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2a Aug. 27, 2022
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
10m Sentinel-2A Sept. 6, 2022
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
50cm WoldView-2 Sept. 16, 2022
PhotoSat
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Jagersfontein, South Africa
2022 Dyke Boundary
50cm WoldView-2 Sept. 24, 2022
PhotoSat
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