Relocation of the Kola-92 deep seismic reflection survey

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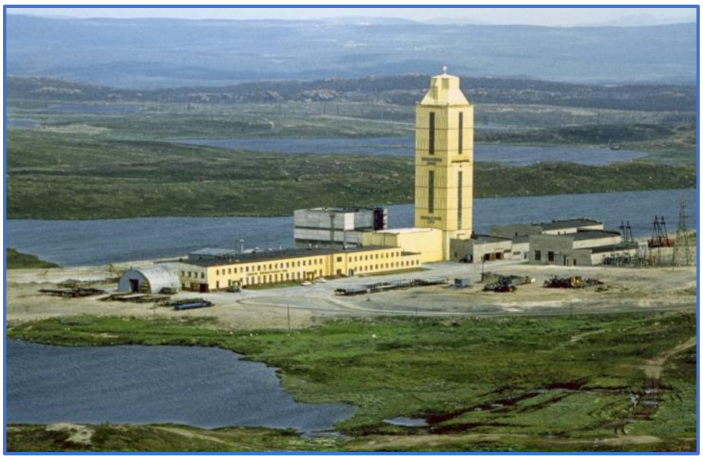

Abstract

The Kola-92 deep seismic reflection survey was a 2D line running from SW to NE through the Kola superdeep well SG-3, the world's deepest borehole. The seismic survey was acquired by an international team in 1992 set up by myself. The team comprised geophysicists from the universities of Glasgow (Scotland), Wyoming (USA), and Bergen (Norway), together with several Russian research institutions.

But the survey was never positioned as accurately as it should have been, dependent mainly upon coordinates marked out by the Russian surveyor on a 1:50,000 topographic map, who then supplied a handwritten set of false-origin (x, y, z) coordinates in metres.

This inadequate information was augmented or modified around the well location by my own notes and sketches, together with limited-accuracy GPS fixes. But the advent of high-resolution satellite imaging, at a resolution of 1-2 m pixel size, has since made it possible to improve upon the locations originally fixed, due to the fact that the survey tracks are still visible in the тайга (taiga - the boreal or snow forest) more than twenty years later.

The relocation exercise results in a new definitive location for all the seismic shot points. They have been combined with elevations taken from a 1 arc-second digital elevation model (DEM). The new elevations are frequently ±20 m from the elevations based on the surveyor's coordinates. Similarly, the positioning difference can be as much as 300 m away from the surveyor's location, and averages out at about 90 m.

The revised locations and elevations may lead to an improved image of the processed 2D reflection image of the main line, and should be used for any future processing of both the single-fold 3D coverage around the well and the 3-component data on the main 2D line, neither of which have ever been processed to date.

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Introduction

The Kola-92 deep seismic reflection survey principally comprises a 38 km long 2D CDP line running from SW to NE through the Kola superdeep well SG-3. There are a further 6 km of 2D source lines at the well, disposed at right-angles to the 2D receiver spread through the well, designed to enable a limited amount of single- and low-fold 3D coverage through the well. The planning, history and logistics are summarised in Smythe et al. (1994), and preliminary results from the CDP profile were published in Ganchin et al. 1998.

Results from the VSP survey conducted in the sputnik (satellite) well during the main field experiment have been published by Carr et al. (1996), and are not further discussed here. I have no information on the Reftek seismometer array which was operated independently of the CDP line by members of the Wyoming team. But since its locations were based on the main line SP locations, they will need relocation as well.

The positional location of the survey shot-points (SPs) has hitherto remained somewhat doubtful. The errors may not have mattered too much for the previously published first-pass processing of the main CDP line, but require to be corrected as far as is feasible, some 30 years on from the field survey itself, for any attempt at imaging the single- or low-fold 3D data around the well. The main implication of the mispositioning of the SPs is that the elevations may be in error in areas of steep terrain changes. Elevation errors feed through to the static corrections, and may thus have degraded the image quality obtained to date.

Datasets originally available

The original survey location comprised a track marked on a 1:50,000 scale topographic map, together with a handwritten table of false-origin (x, y, z) coordinates marked out by the Russian surveyor Volodia (his full name is not known). He used the map to position the SPs, and then read the elevations from the map contours. His locations were augmented or modified around the well by my own notes and sketches.

Mr Chris Humphreys, in charge of the Wyoming doghouse (recording cabin), used a Magellan GPS receiver to read off the doghouse position every time it was moved up the line by 30 SPs, but he only started doing so at SP 496, some 15 km along the line from the SW end. I also used this receiver to take various fixes around the well once the CDP line had progressed to its final position at the well.

A large-scale paper plan of the wellsite buildings was available. It lacks a scale and grid. How all these datasets were used and reconciled with the satellite imagery is discussed below.

The topographic map

We (the western scientists) were not given a copy of the topographic map. It was stamped секретный (sekretniy = secret), and although the USSR had collapsed a few months previously year (1991) a Soviet-era mentality still persisted somewhat with the Russian Federation scientists. However, I persuaded one of them to bring the map into a locked room and hold it up to the wall to enable me to photograph it. **Figure 1** shows an example (all figures are appended at the end of this report). The fingertips confirm that the pitch of the 1 km grid is 2 cm, so the map is indeed at 1: 50,000 scale. But it can be seen that the printed northing of 7693 mismatches Volodia's handwritten value of [76]89. A similar mismatch applies to the eastings.

Eventually it was realised that the map uses a projection of the Soviet Unified Reference System (SURS), and the false origin of the surveyor's table of local (x, y) coordinates could be converted to a global system. Between 1993 and 1997 the SPs were plotted and corrected using an Oracle database management system and map-making using Generic Mapping Tools (GMT). But the problem of which map datum to use had never been resolved satisfactorily, because mismatches of the order of 100-200 m still remained between datasets brought in from different map sources. I used an *ad hoc* datum correction to try to reconcile map data from different sources.

The GPS fixes

The GPS receiver was a Magellan NAV 1000. It is believed to be the first commercial handheld GPS receiver, entering the market in 1989. It cost $3000. The full constellation of 24 GPS satellites was completed only in 1993, so we were early players in the use of GPS for geophysical surveying. But the selective availability (SA) function, added to the signal used by civilian users, deliberately degraded the accuracy of the positioning by up to 100 m horizontally. SA was removed in 2000.

The Magellan receiver records satellites sequentially, and can take a few minutes to find the minimum of three satellites needed. The 3D mode was used, which is less accurate than 2D. The reading was logged in the observer's log sheets, but it is not stated whether more than one reading was taken. It would appear not. It has an option for setting the map datum, but which datum was used was not recorded until I took readings around the wellsite at the end of the survey. We did not understand the significance of the datum at that time, and which one was used. The two likely candidates could have been NAD27, the North American datum (since the instrument came from Wyoming), or alternatively WGS84, for the GPS satellite system.

Figure 2 shows the positions along the line relative to the final corrected line location. It shows the lat/lon fixes converted to the map projection assuming two different datums. **Figure 3** shows detailed maps of the neighbourhood of each fix. If we assume that the NAD27 datum was used (blue dots in **Figures 2** and **3**), then the first six fixes (counting from south to north) agree with the final line location very well, as do the GPS fixes for SPs 796.5 and 886. The alternative, using WGS84, yields positions for these eight SPs that are consistently 200 m to the NW (green dots). But on the other hand fixes 685.5 and 826 match the CDP line well assuming that the WGS84 datum was used. In conclusion, we have to assume that the datum was switched between NAD27 and WGS84.

The GPS fixes interpreted in this way were not used to reposition the line, which was done based on the satellite image tracks. However the locations of the SPs along the line were adjusted slightly to achieve a good fit to the GPS fixes, while also retaining the 50 m SP spacing as far as possible.

Fixes around the well

The paper plan of the wellsite buildings is shown in **Figure 4a**. North is on the left. It has no scale, nor grid, but is at about 1:1500. The arrows at the bottom depict grid north, true north and magnetic north. **Figure 4b** shows the plan rectified to the grid using features from the plan, such as building corners and the river, matched to the Google Earth image. The well was sited at the centre of the cross formed by the buildings. The drilling tower had been demolished by the date of the Google Earth image, 2017, which is why there is no shadow of the tower on the image. Earlier Google Earth images do not have enough resolution to show the buildings clearly, with or without the tower.

I took a number of GPS fixes using the Magellan receiver at locations around the wellhead (red dots in **Figure 4b**). They all used the WGS84 datum, and were each averaged from 50 fixes. The standard deviation σ settled down to ~15 m after just a few readings, so taking 50 fixes at each location became redundant.

New datasets

The datasets that have become available within the last decade include digital elevation models with a high enough resolution (1 arc-second, or a nominal 30 m) to be useful. These are discussed below. In addition there are several surface imaging datasets with spatial resolution of less than 2 m. However, I have been restricted to using what is freely available.

The best free image set is from Google Earth Pro. It covers the northern half of the survey line (red outline in **Figure 5a**). Here it appears to have a pixel resolution of less than 0.5 m, and is easily capable of showing survey tracks of around 3 m width. But south of Shulg'Yaur inlet the effective resolution available on Google Earth is 5 or 10 m, and therefore incapable of revealing survey tracks.

From Shulg'Yaur lake south to Oval lake I have used preview images available on the commercial UP42 website. This dataset, for which the coverage used is shown by the blue box in **Figure 5a**, appears to be the same as the best Google Earth Pro images, except that in the free preview mode one cannot zoom in as far.

Overlapping with the UP42 imagery, and taking us to the south end of the line, I have used preview images from the Terraserver website, which I downloaded in 2014 (green box in **Figure 5a**). These are no longer available online. They appear to have a similar sub- 1 m resolution as the Google Earth Pro data, but are greyscale, not full colour.

Panels from the Google Earth Pro display a geographic grid. The projection is Mercator, using the WGS84 datum, so it is fairly simple to register the panels for addition to the Global Mapper 19 mapping program. But the other two datasets have no grid markers, so I had to stitch together lines of panels, then register the resulting image by matching it to the 1:50,000 topographic map.

Relocation results

The image datasets described above have enabled the probable track of the survey line to be confidently identified, thirty years on, over about 80% of the survey line (blue lines in **Figure**

5b). The most serious gap is at the southern end of the line from Lake Ruossel'Yaur to Oval lake, SPs 169-325, about 9 km long, where no tracks could be identified. Here we have to accept the surveyor's coordinates as being accurate, with only very minor modification. Fortunately this line segment is very straight, so the original SPs are likely to be good.

The other main gap in the direct identification of tracks is from the well north to the Nikel road, SPs 916-961, 2 km long. The problem here is that the ground is rocky and bare, and traversed by many other tracks. However, my own notes and sketches for this rather twisty line segment allowed a reasonably accurate estimate of the SP locations, probably to within 20 m.

The relocated SPs are probably all now accurately positioned to within about 25 m of their actual positions, or about half a shot-point interval, This is adequate for seismic processing. **Figure 6** shows a comparison of the original surveyor's SPs (red dots) compared with the relocated SPs (green dots, numbered). The figure shows the line split into four parts labelled (a) to (d) from SW to NE, respectively. The grid is at 1 km spacing. It is evident that there have been serious positioning errors amounting to several hundred metres in some localities.

Elevations

The relocated SPs been combined with elevations taken from a 1 arc-second digital elevation model (DEM). I have used the DEM developed by Jonathan de Ferranti in the first decade of this century. The DEM for the present region of interest was derived from digitisation of the elevation contours on topographic maps, and not from the Shuttle Radar Topography Mission (SRTM) data of 2000, which he used for most of the rest of the world. The panel covering the region of interest is N69E030, downloaded in 2014.

I compared this dataset with the more recent free 1 arc-second DEM made available by the Japan Aerospace Exploration Agency (JAXA). This is based on satellite data only. Although superficially it looked to have better resolution, the heights of the water in the many lakes in the area were very variable. In conclusion de Ferranti's DEM is to be preferred.

Details of the relocation

We have no good imaging information for the southernmost segment of the line, SP 169 to about SP 320. The surveyor's fixes correspond closely to the originally planned straight line, and the terrain is fairly gentle. So we have to assume that the original survey is correct. However, between Round and Oval lakes the surveyor mapped in a detour of about 300 m to the SE side of the straight line. Here there is imaging evidence both for the original straight path, about 100 m east of the planned straight line, and for a slight additional deviation to the east. **Figure 7** shows that the surveyor's detour was made to avoid going over the top of a steepish hill. So I have accepted the surveyor's detour, but going north I bring the relocated track back onto the straight line as marked by good imaging, and not back to the surveyor's location. The existence of a continuous straight track over the hill, as seen from the satellite imaging (blue line in **Figure 7**) implies that the caterpillar-tracked vehicles must have initially marked out that track. However it was decided later to avoid the steep local gradients by deviating the survey to the east.

Going north, **Figure 8** shows a typical example of the track visibility in the satellite images, in this case the Terraserver dataset**. Figure 8a** is unmarked except for the surveyor's locations (red dots), and **Figure 8b** shows the marked track (blue line) used to fix the final relocated SPs (green labelled dots).

Figure 9 shows the detour I have named Big Kink 1 (located in **Figure 5**). This detour was taken to go round low boggy ground, but the surveyor's version is generally too far NW by more than 100 m. The detail in the inset shows several parallel clear tracks running ENE, whereas the surveyor's fixes place the line running north at this point (red line in the inset).

North of Shug'Yaur inlet the Google Earth Pro images are available (**Figure 5a**), and the image of the track is very clear. The planned track deviating to the west round a big hill just south of the well is shown by the pencilled line on the topographic map in **Figure 10a**. The surveyor's fixes (red dots) follow this line quite closely. However the Google Earth image clearly shows that the track lies over 100 m to the east (**Figure 10b** and inset).

When we reach the well there are significant differences between the surveyor's positions and the relocated positions (**Figure 11**). However, tracks are either not apparent on the images, or else there are many tracks due to the traffic around the well. The former case is due to the fact that west and north of the well there is bare rocky outcrop. Repositioning here was aided by by own notes and sketches. **Figure 11** shows that just NW of the well the surveyor's coordinates are in error by over 100 m.

Just SW of the well was the only locality where the vibroseis array departed from the main receiver line. The vibs went anticlockwise around the east side of the lake, between SPs 1911-1923, whereas the receiver array ran straight across the frozen lake in a northerly direction, but no geophones were planted on the ice at SPs 913-916 inclusive.

Lastly, the vibrator stations running along the road east from the well, and along the Nikel Road to the north, can be precisely fixed because of these roads. This is shown in **Figure 12**, which serves to demonstrate that even here, with good natural and built features to rely on, the surveyor's coordinates are locally in error by up to 200 m.

Comparison of original and relocated SPs

Figure 13 (upper) shows DEM elevation along the main line, SPs 191-961. Note that the 'Big Hill' labelled is actually a very steep local south-facing escarpment between SPs 735-740 where we had great difficulty in hauling the vibrator array through the snow up to the top using caterpillar tractors pulling and pushing. This episode is shown in the video of the fieldwork (Smythe and Brierley, 1992).

The middle graph of **Figure 13** shows the height difference (new-old) along the main line. The new elevations are frequently ±20 m from the elevations based on the surveyor's coordinates. Similarly, the positioning difference (**Figure 13**, bottom) can be as much as 300 m away from the original location, and averages out at about 90 m.

Conclusions

The revised locations and elevations are in many places significantly different from those estimated by the original surveyor. Use of the relocated position data may lead to an improved image of the processed 2D reflection image of the main line, and should be used for any future processing of both the single-fold 3D coverage around the well and the 3-component data on the main 2D line, neither of which have ever been processed to date.

References

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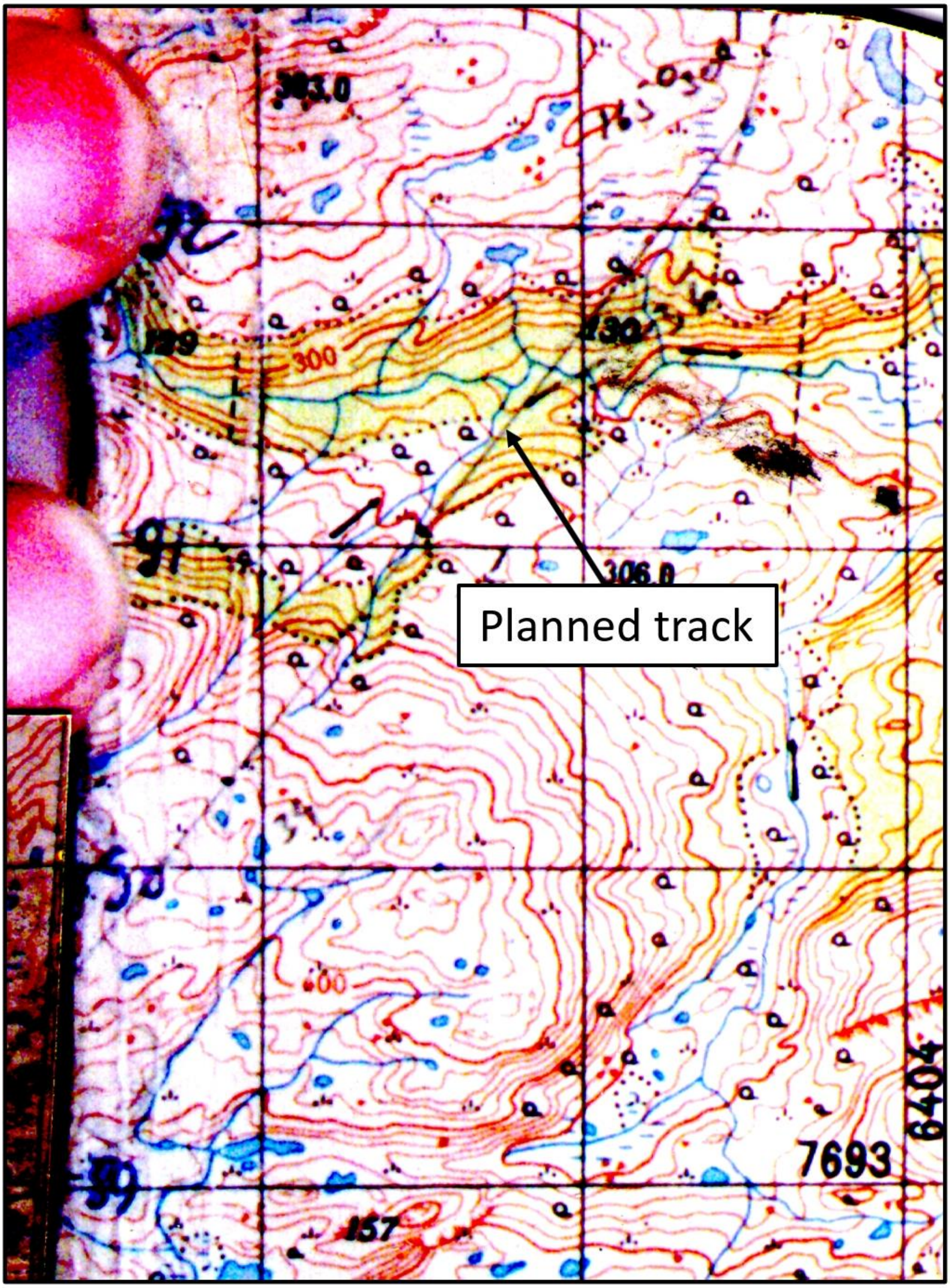

Figure 1. Example of the 1: 50,000 topographic map. The track of the seismic line as planned in 1991 is pencilled in. The north side of the stream valley running east-west between the fingertips, and highlighted by the 300 m contour, is the 'Big Hill' escarpment.

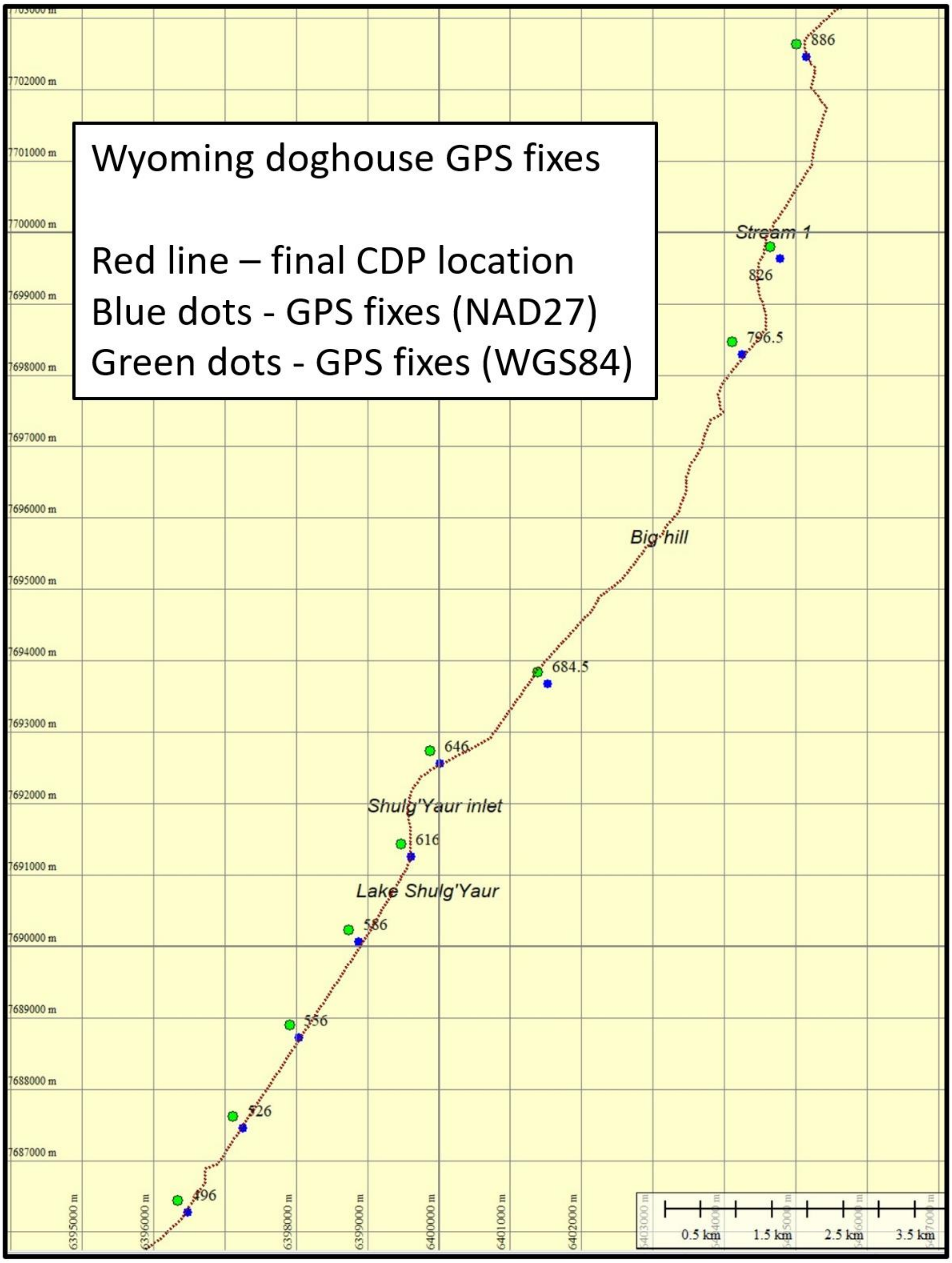

Figure 2. Summary of the GPS fixes along the main line (shown by red dots) at the Wyoming doghouse. The alternative positions, using a NAD27 datum or a WGS84 datum, are shown by blue and green dots, respectively.

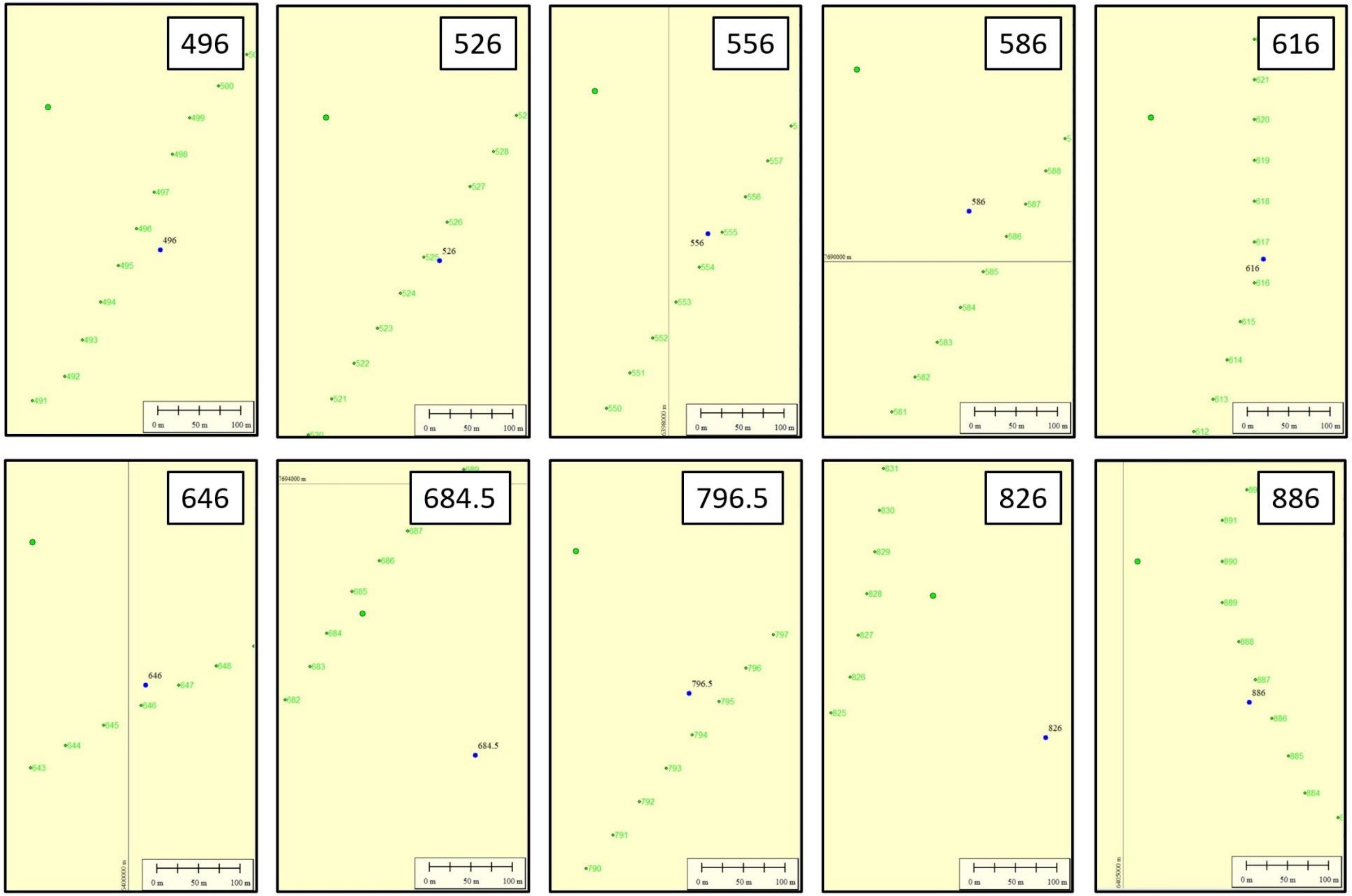

Figure 3. Details of the ten GPS fixes taken at the Wyoming doghouse. Green labelled dots are the final SPs. Blue dots are GPS fixes assuming a NAD27 Datum. Green dots are the fixes assuming a WGS84 datum.

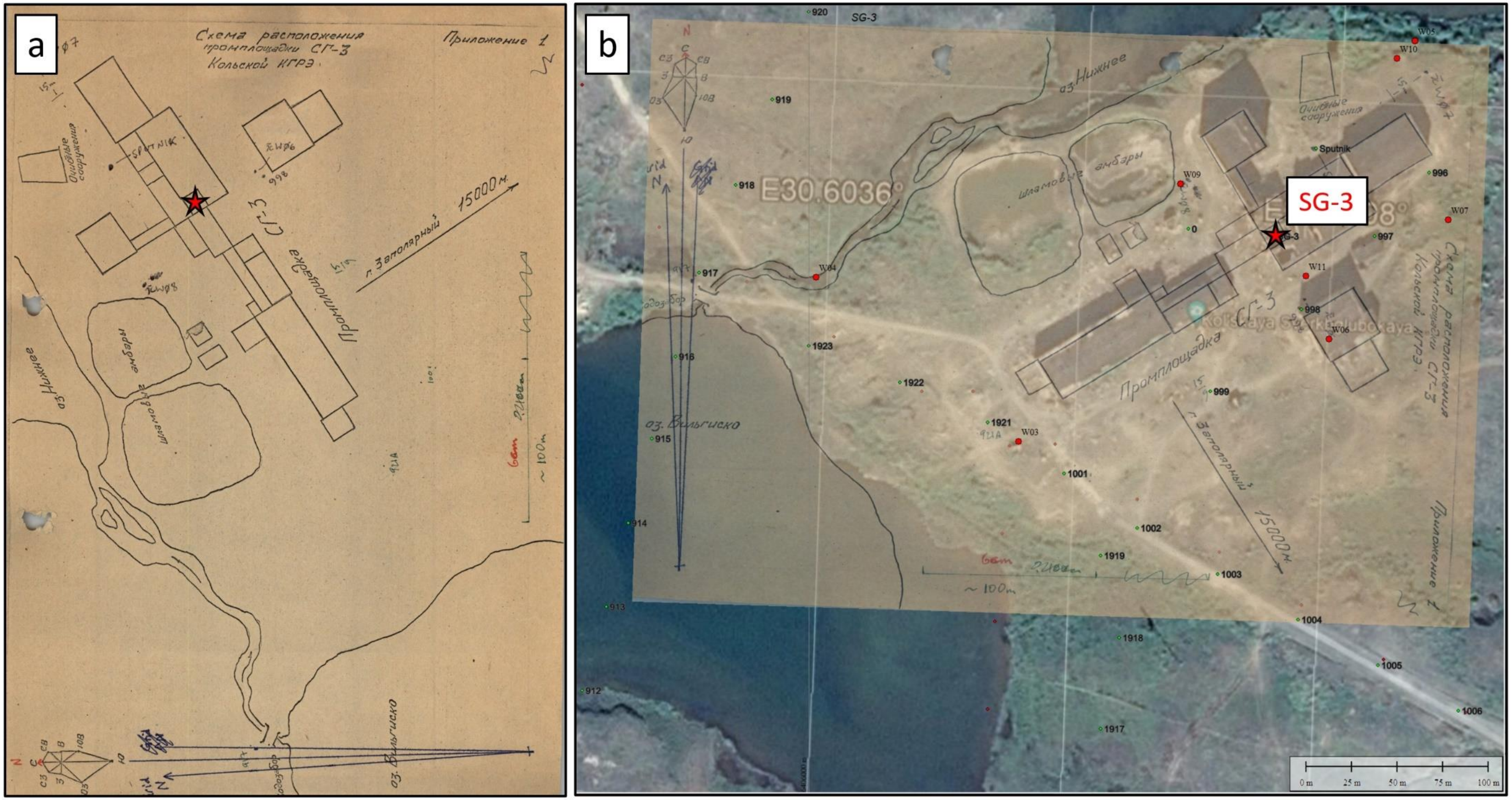

Figure 4. (a) Paper plan of the wellsite buildings. North is on the left. (b) Plan rectified to the grid using features from the plan, such as building corners and the river, matched to the Google Earth image. The wellhead of SG-3 is shown by the red star.

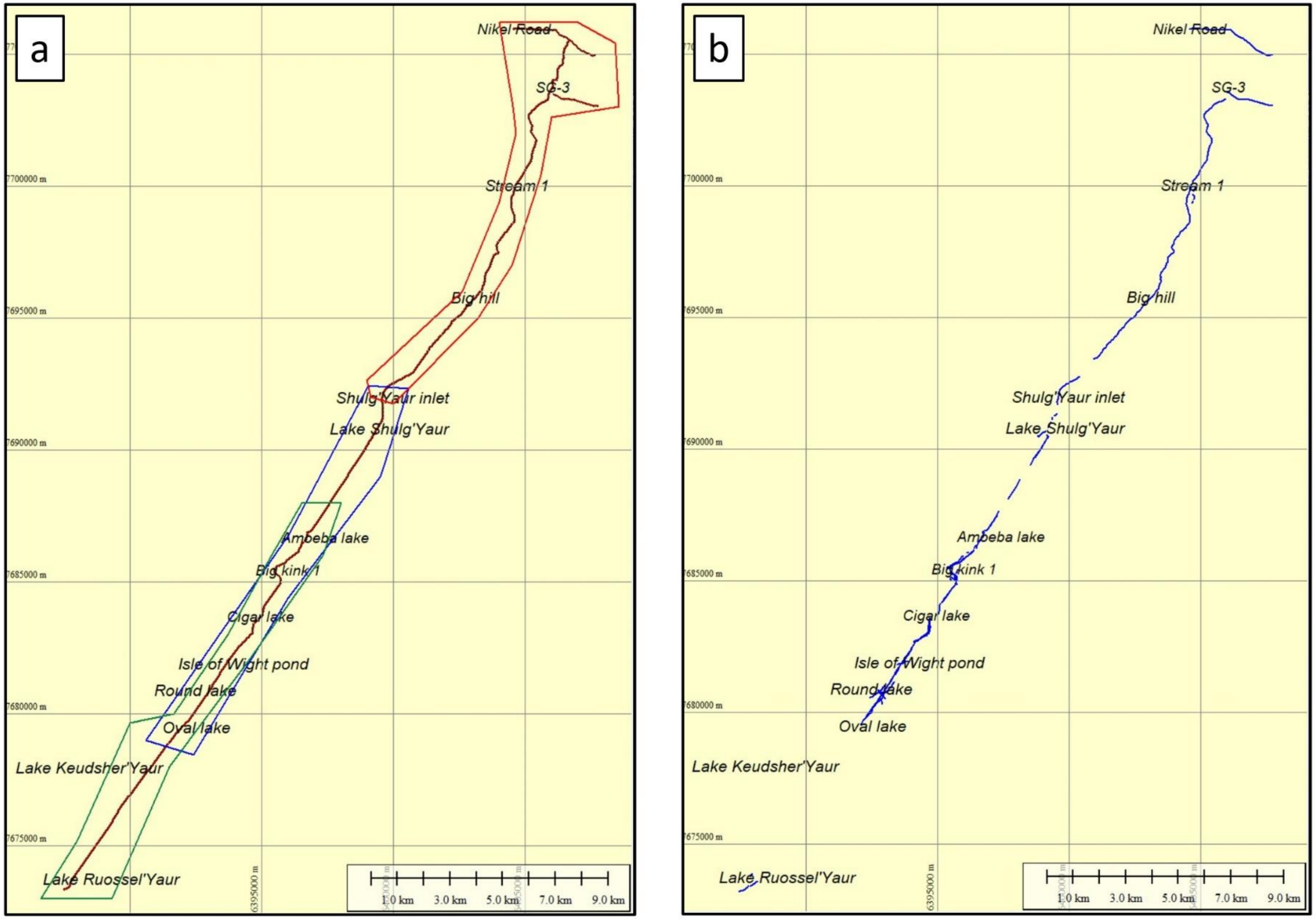

Figure 5. (a) Availability of satellite images: red box – Google Earth Pro, 2021; blue box – UP42 preview images, 2021; green box – Terraserver preview images, 2014. (b) Summary map of tracks identified on imagery. It is nearly complete apart from the main line going north from the well, and at the SW end, south of Oval lake.

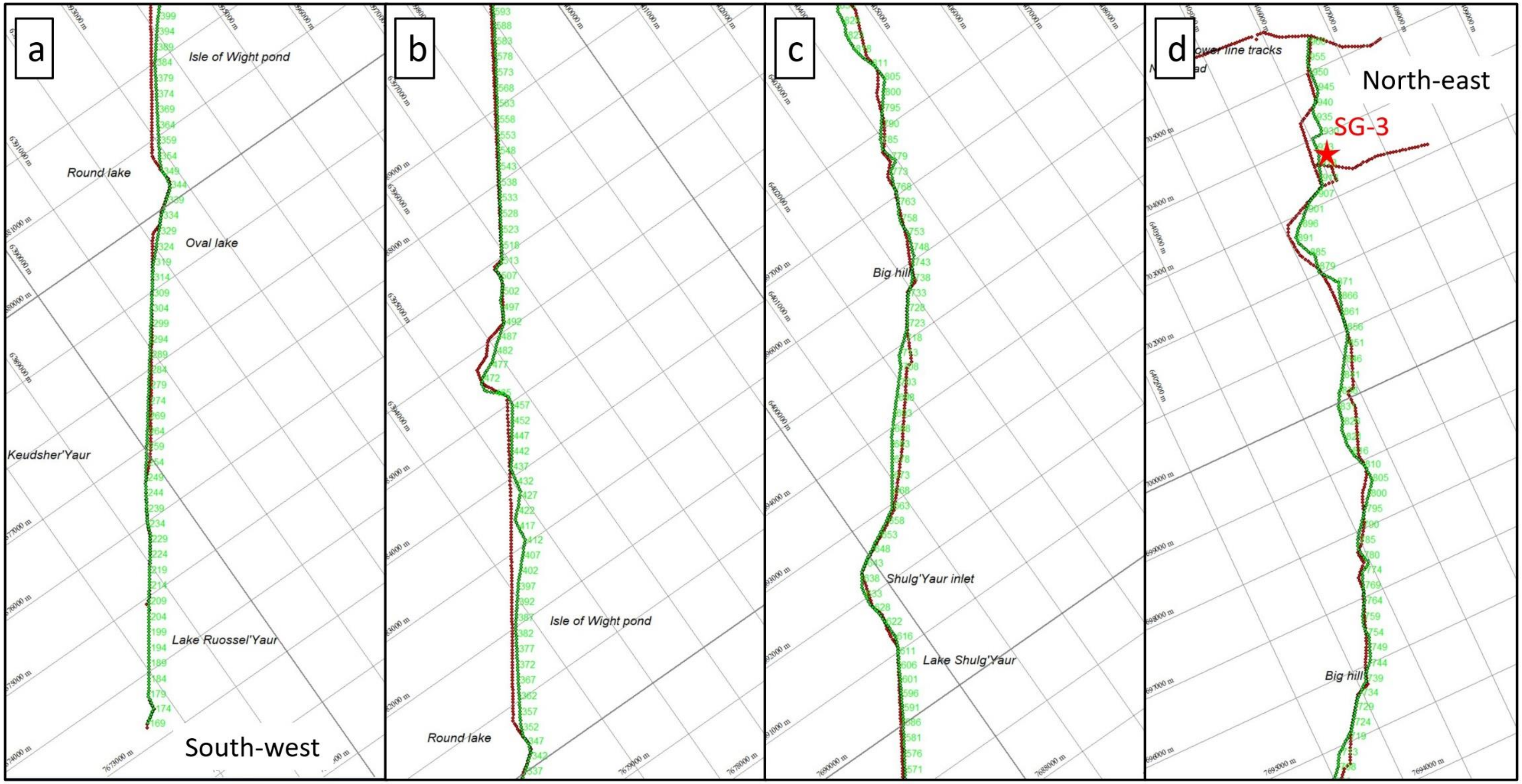

Figure 6. Original surveyor's SPs (red dots) *vs.* final corrected SPs 2021 (green dots) for the main line, which is split into four overlapping sections (a) to (d), from SW to NE, respectively.

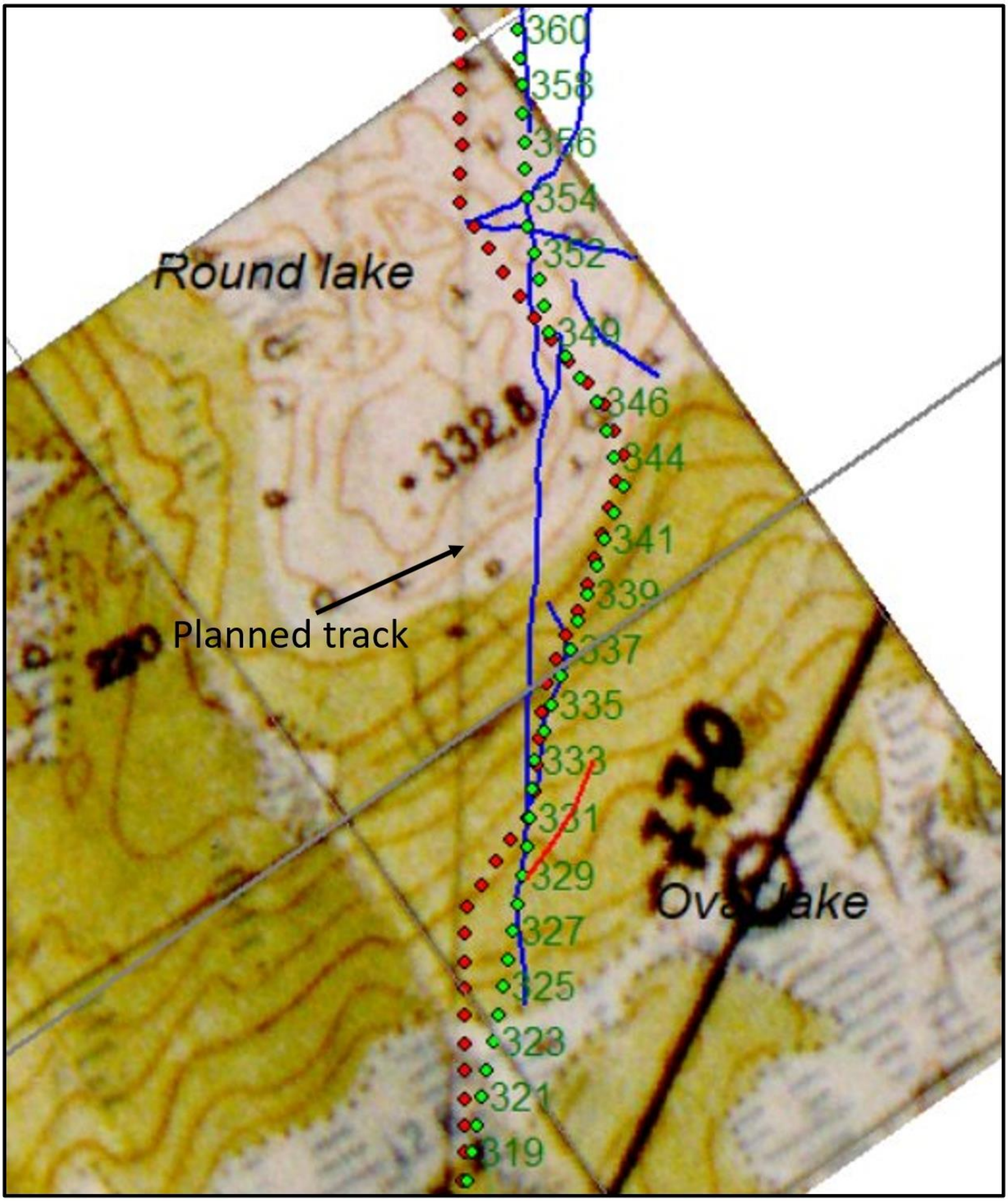

Figure 7. Detail between Oval and Round lakes, showing the detour round a hill. Red dots – surveyor's locations; labelled green dots – relocated SPs. Blue and red lines indicate tracks identified from satellite imaging.

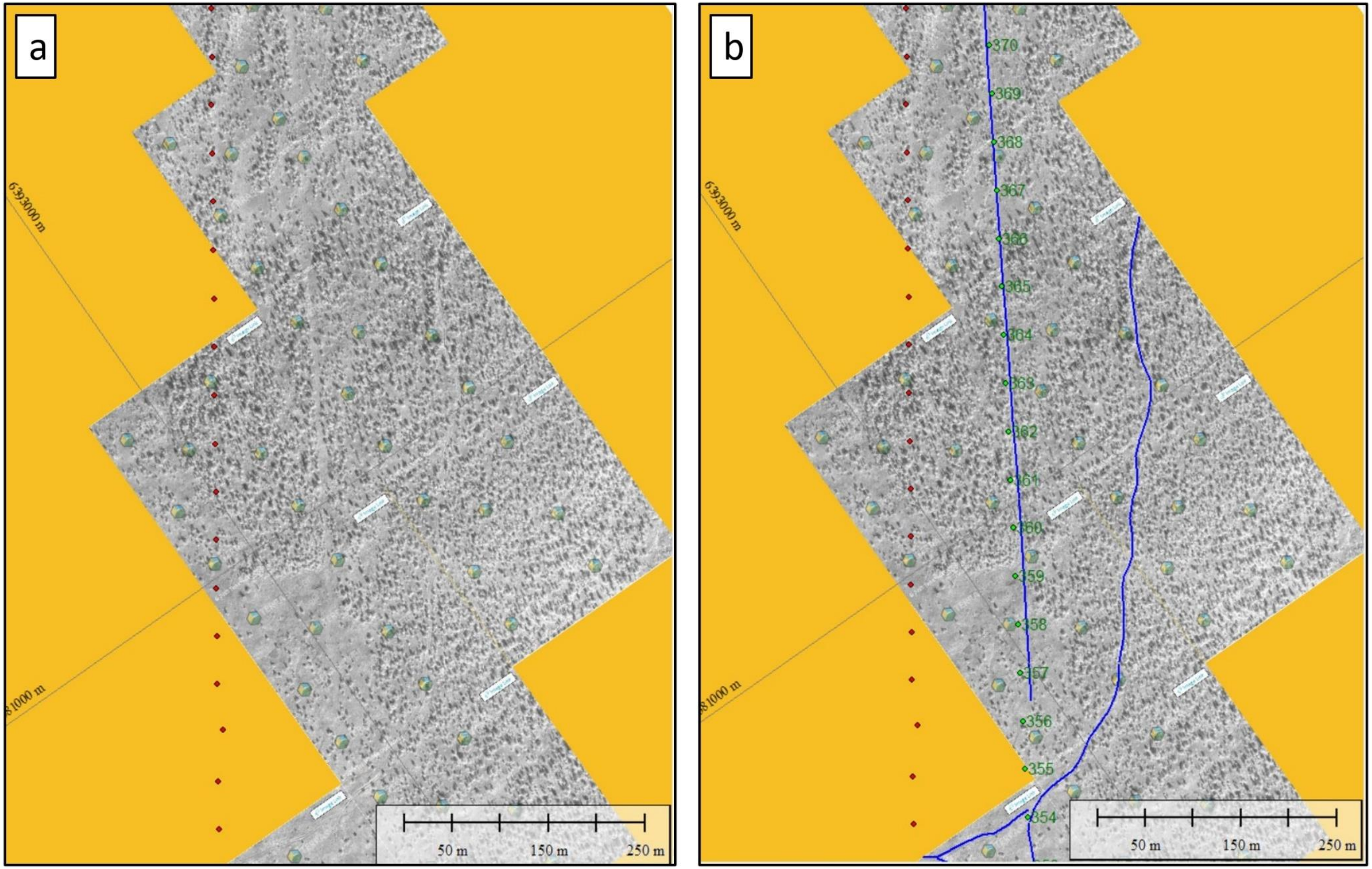

Figure 8. (a) Terraserver preview images stiched together. The surveyor’s line is shown by the red dots. (b) Identifiable tracks are marked by blue lines. The final SPs are marked by green dots and labelled.

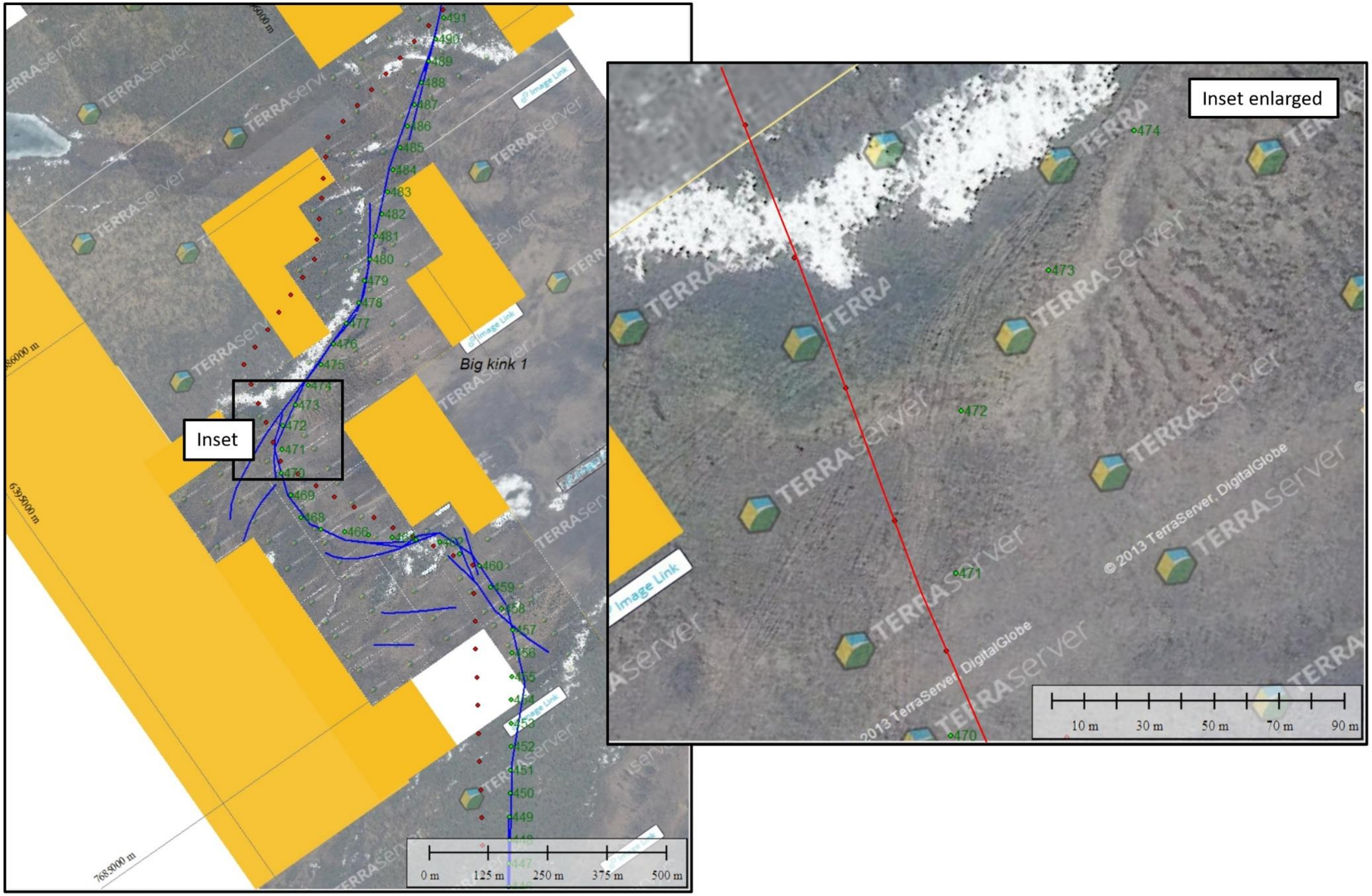

Figure 9. Terraserver images in the Big Kink 1 locality. Red dots – surveyor's SPs; labelled green dots – SP final relocations based on identified tracks (blue lines). The inset enlarged shows the clear track images. The surveyor's SPs are connected by the red line.

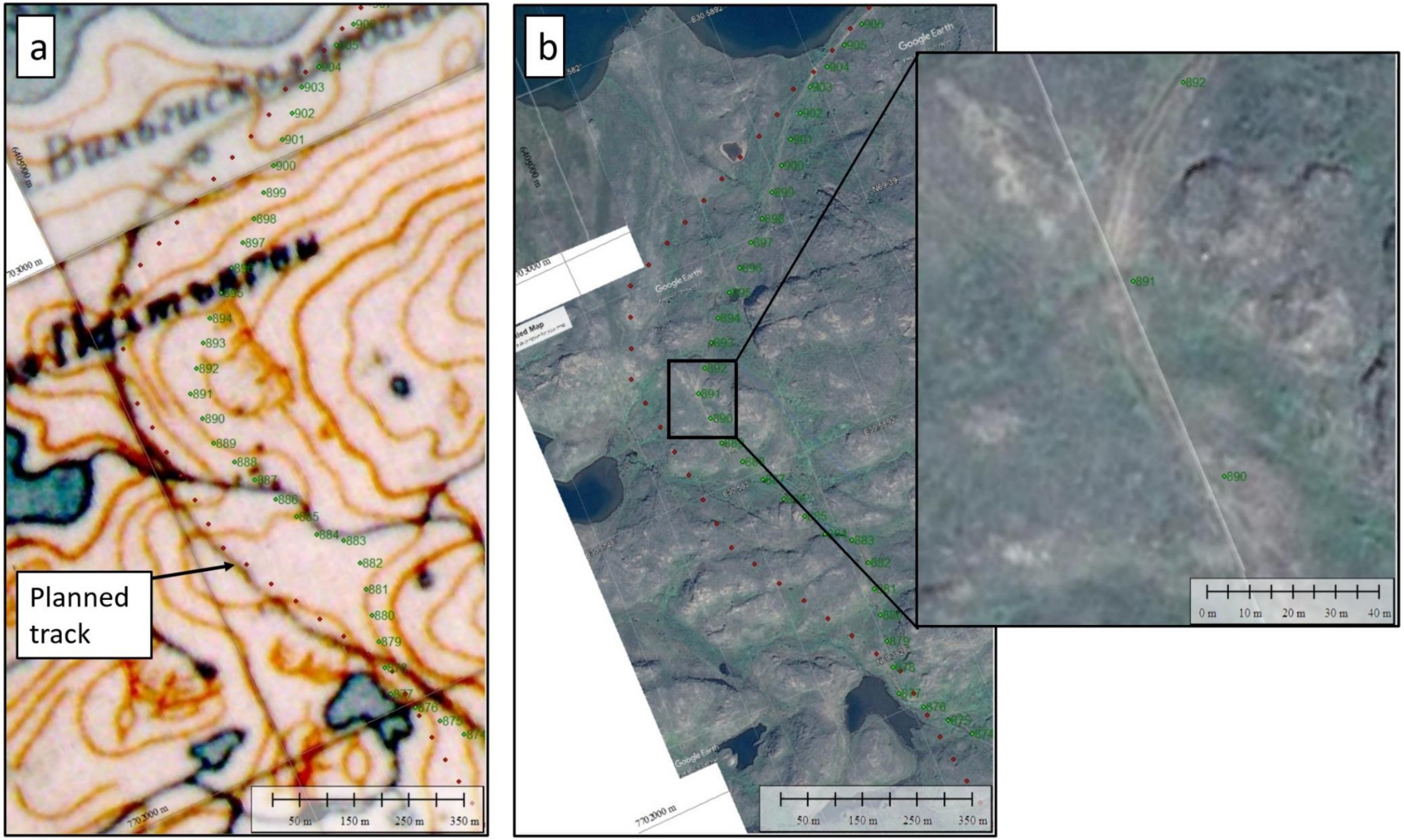

Figure 10. (a) Topographic map of the area just south of the well, showing the planned track marked by pencil, with the surveyor's locations generally following it. North is to the upper left. (b) Google Earth image of the same area as (a). The true line location lies at least 100 m to the east, as shown by the clear image of the track. The inset of (b) shows a close-up of the track. The straight white line is a meridian.

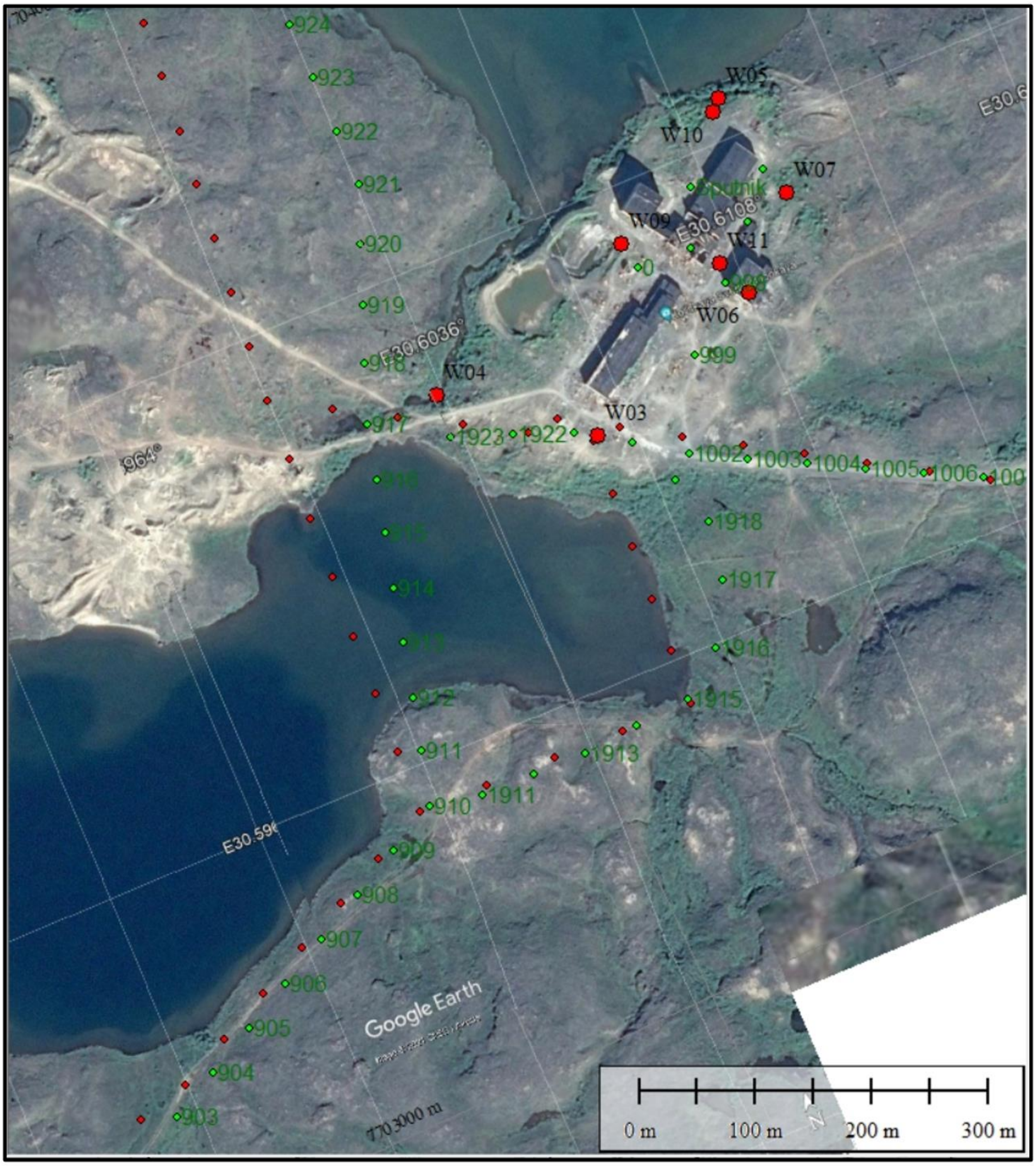

Figure 11. SPs around the wellhead. The source array went round the edge of the lake (SPs 1911-1923). The receiver array went straight across the frozen lake (SPs 910-917).

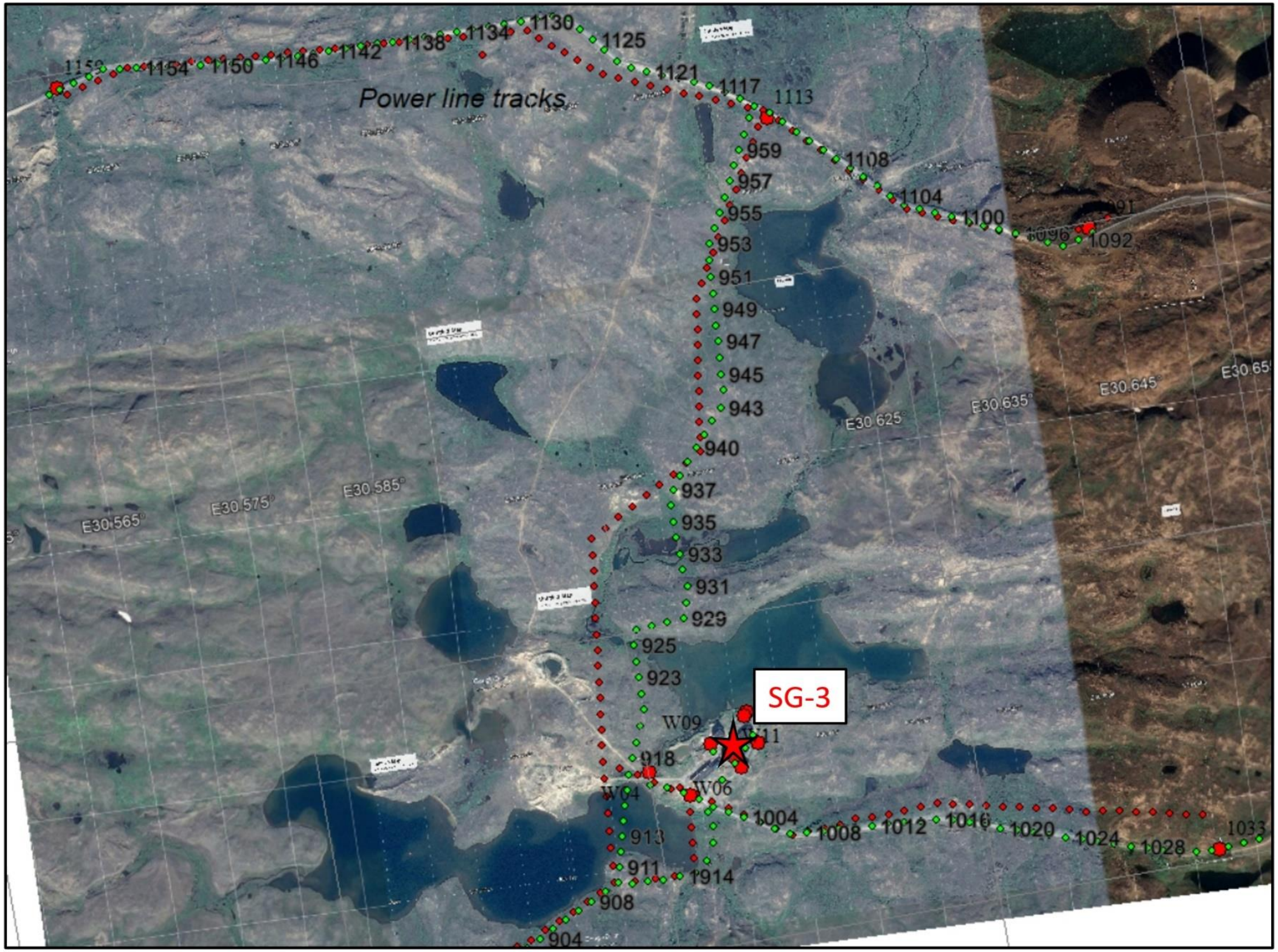

Figure 12. SPs on the roads around the well. Red dots – surveyor's original locations; labelled green dots – relocated SPs. The well is marked by the red star.

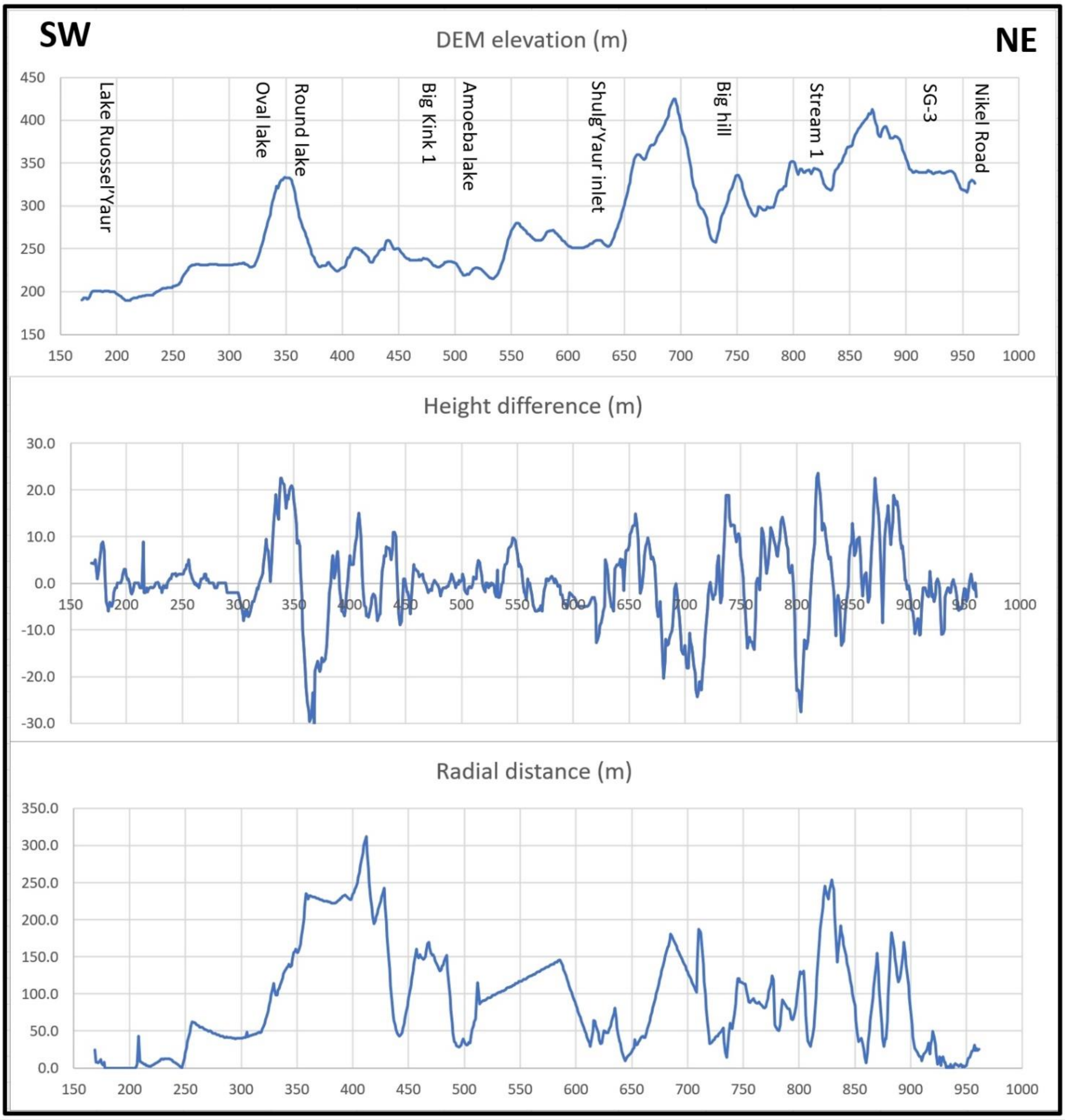

Figure 13. Top – DEM elevation along the main line, SPs 191-961. Middle - height difference (new-old) along the main line. Bottom - magnitude of the radial distance vector from surveyor's SP to relocated SP.