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Seismic Monitoring of Inundation of the Glendoe Hydro Scheme Reservoir

Earth Hazards Programme

Open Report OR/12/062

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Seismic Monitoring of Inundation of the Glendoe Hydro Scheme Reservoir

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) . It describes an experiment to monitor possible induced seismicity at the largest reservoir to be impounded in Britain for decades.

Acknowledgements

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Contents

Summary

Impoundment of reservoirs is known to sometimes cause earthquakes. At Glendoe in the Scottish Highlands the first large-scale hydro-electric power station to be built in the UK in almost 50 years was built in 2007/2008. In May 2008, a small network of seismometers was installed around the area due to be flooded at Glendoe to monitor any possible seismicity and these stations were maintained for a year after impoundment. Although a number of local earthquakes were recorded with good signal to noise ratios, no seismicity was recorded that can be attributed to the reservoir. This is perhaps because the dam is low, with a maximum water depth of 35m, whereas most reservoir induced seismicity has been observed at dams with water depths of over 100m.

1 Introduction

A small array of seismometers was deployed to monitor possible induced seismicity associated with filling of the reservoir behind a new hydroelectric dam at Glendoe. It is well established that filling large reservoirs can trigger earthquakes (Talwani, 1997). Such induced seismicity often occurs soon (between a few days and a year) after the reservoir reaches its maximum depth. Impoundment of a reservoir can trigger seismicity in two ways, an immediate response to loading, and a delayed response due to the diffusion of pore pressure (Rajendran and Talwani, 1992; Simpson et al., 1988). The first case is the most obvious with events occurring while reservoirs are filled or soon after. These earthquakes tend to be directly beneath the reservoir or very close. The second type of seismicity can continue for years and may be related to changes in water level in the reservoir (Simpson and Negmatullaev, 1981) . These earthquakes can occur up to 10 km from large reservoirs. Statistical analysis of reservoirs worldwide (Baecher and Keeney, 1982) has shown that depth is the most important parameter when assessing the likelihood of reservoir induced seismicity. This study suggests that the chance of seismicity being induced by a reservoir only 35 m deep is negligible. However, they mainly consider earthquakes large enough to be widely recorded or felt, rather than small events that can only be detected by a network local to the reservoir. An example of a shallow (31 m) reservoir that was closely monitored is that at Acu Dam in Brazil (Ferreira et al., 1995). Here monitoring started some years after the reservoir was impounded but many small events were detected. This reservoir, however, has a volume 200 times greater than the reservoir at Glendoe.

In May 2008, a small network of four seismometers was installed around the area due to be flooded at Glendoe to monitor any changes in background seismicity and investigate the occurrence of any events induced by the impoundment of the reservoir. These stations were maintained for a year after impoundment. In this report, continuous data recorded on the four seismometers are analysed in order to detect any events and determine their locations and other characteristics.

The Scottish and Southern Energy Glendoe Hydro Scheme is the first large-scale conventional hydro-electric power station to be built in Scotland for almost 50 years. A dam built across the river Tarff 600m above Loch Ness forms a reservoir 900 m by 1800 m at its maximum extent. Water from an area of 15 square kilometres drains naturally into the reservoir and a system of underground pipes and tunnels gathers water from an additional area of 60 square kilometres in the surrounding hills. Up to 12 million cubic metres of water are stored, depending on operation of the power station. The dam is long and low, with a length of 960 m and a maximum height of 35 m for a short stretch in the river valley. The power station is housed about 6 km from the reservoir in a cavern 250 m below ground level. Work on the reservoir began in August 2006, and the dam was completed in September 2008, when impoundment started. The reservoir was full by early December 2008, when power generation began. Figure 1 shows the dam before and after impoundment.

Figure 1: View of the reservoir from site GQUA in May 2008 and in May 2009.

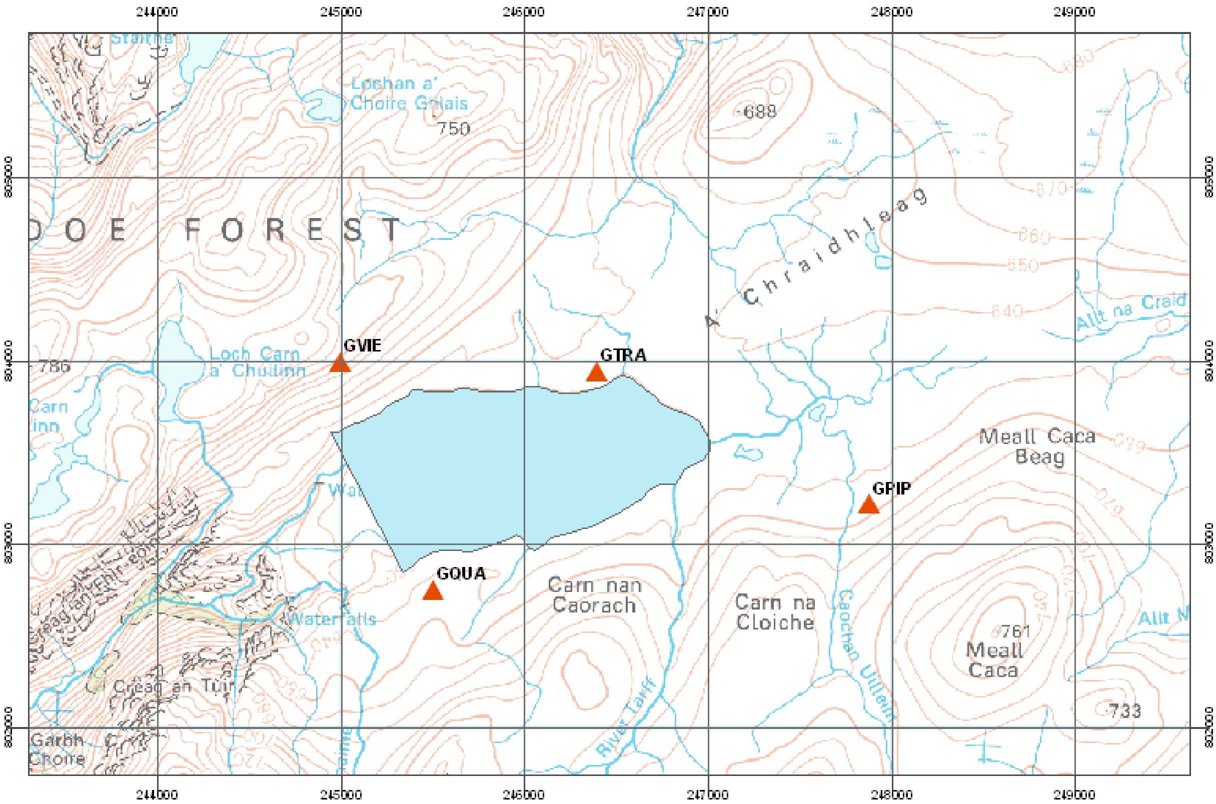

Figure 2: The locations of the four temporary seismic stations. Glendoe reservoir is shown at its approximate high water level.

2 Network Deployment

The network was installed over two days on May 13th and 14th 2008. Four stations were deployed (Figure 2): one three component, broadband instrument and three single component, short period instruments. The broadband station was situated near to the viewing platform above the dam and was given the code GVIE. Here, a Nanometrics Trillium 240 seismometer, with a lower corner period of 240 seconds, was installed alongside a Nanometrics Taurus digitiser. The sampling rate was set to 200 Hz, giving an upper usable frequency of 100 Hz. At the other three sites, Geotech S-13J seismometers were installed. These are single vertical component instruments with a lower corner frequency of 1 Hz and were digitised at 200 Hz using Reftek 310-01 digitisers. At all the sites, power was provided by solar panels and batteries. Data were stored on the digitisers' flash memory and downloaded on regular maintenance trips. The co-ordinates of the stations are given in the appendix. The short period stations were removed in spring 2010 after being without power over the winter. GVIE remained to contribute to the national network as there is no other station close by. However, it is not ideal for this purpose as there are no communications and data need to be downloaded periodically. At some point in the future a new permanent site will be installed nearby and GVIE will be decommissioned.

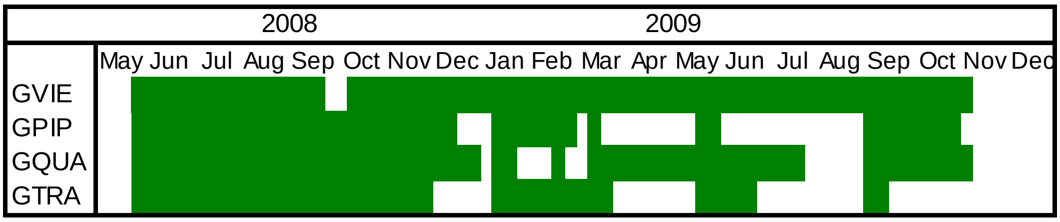

Table 1: Weeks when each station was functioning.

Table 1 shows when each station was working. As can be seen, there were problems with all of the short period sites from the start of the first winter onwards. This was largely due to the combination of bad weather and solar panels (Figure 3) although problems with the Reftek digitisers were also an issue.

Figure 3: Solar panel at GVIE in December 2008. The solar panel here was cleared but the other three sites were unreachable and so remained without power until the new year.

3 Processing

The algorithm used to detect events is the same as that used in the Earthworm acquisition package (Johnson et al., 1995). First the traces were filtered between 1 Hz and 25 Hz to remove noise outside of the range of the signal. Then at each station a 1 second, short-term average (STA) of the trace is calculated and 100 of these STAs are averaged to get the long-term average (LTA). In addition to these two `straight' averages, there are corresponding rectified averages. The short-term rectified average (STAR) is taken from the absolute value of the difference between the trace and the LTA, averaged for one second. The long-term rectified average (LTAR) is the 100 second average of STAR.

These four averages are combined to determine the station trigger status:

eta = STAR - *ratio* * LTAR - | STA - LTA | - *quiet*

If *eta* is greater than 0.0, the station is considered triggered. The constants *ratio* and *quiet* were set using local earthquakes recorded on the Glendoe stations, as well as on other stations of the BGS network. Values were found that allowed the stations to trigger on the local events but which minimised the number of false triggers in the same day. Different values were needed for each site:

- GVIE *ratio* = 3.0, *quiet* = 5.0
- GPIP *ratio* = 2.5, *quiet* = 3.0
- GQUA *ratio* = 3.0, *quiet* = 5.0
- GTRA *ratio* = 3.3, *quiet* = 5.0

At times when three or four stations were operating the condition was then applied that at least two of the stations should trigger within the same 10 second window. These network triggers were then looked at by eye. When only one or two stations were working every station trigger for GVIE was checked by eye.

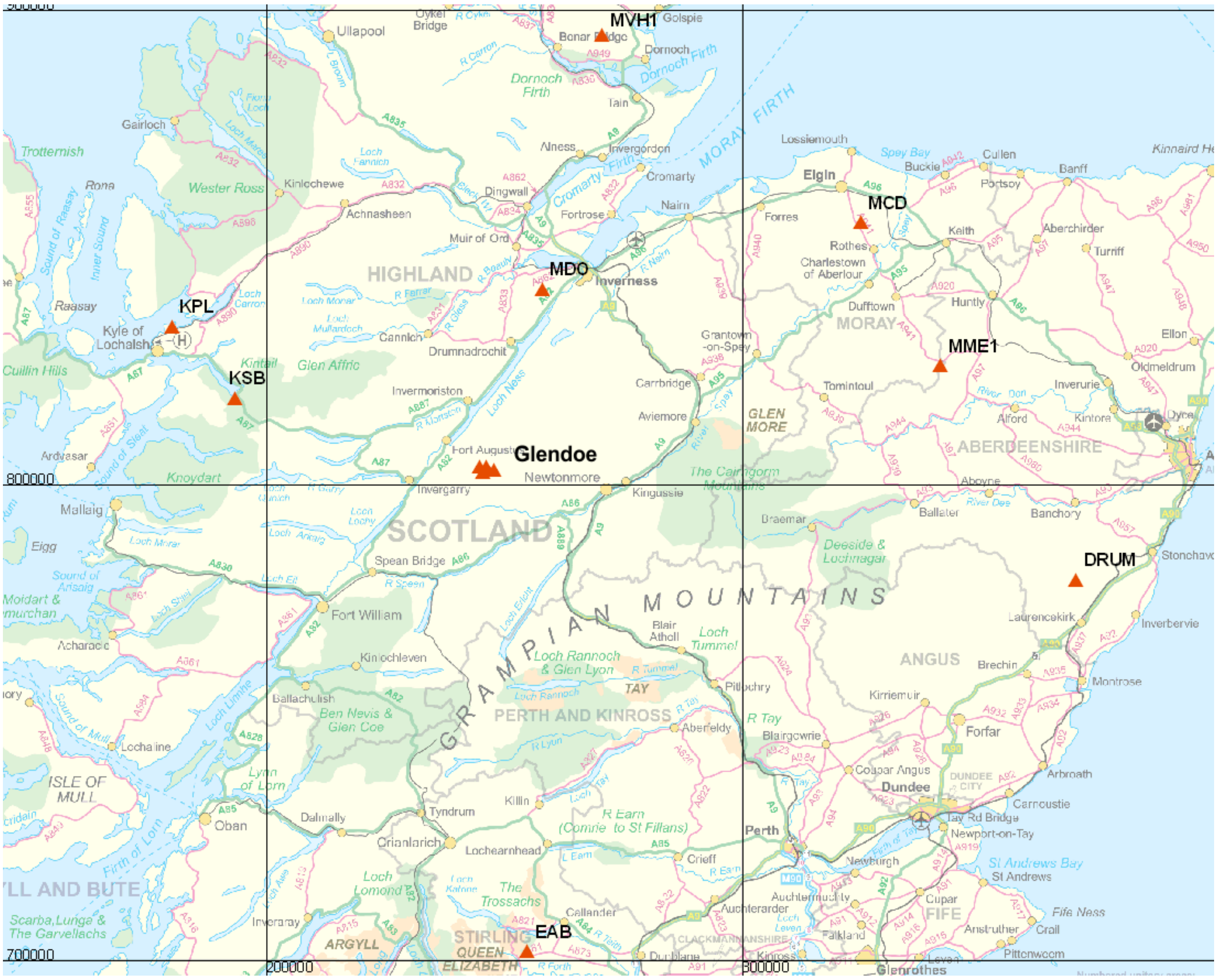

Figure 4 Contributing stations of the permanent BGS network that were used to refine locations made by the Glendoe network.

4 Results

A search was made for events between 1st September 2008, the month when impoundment started, and the end of October, 2009. For those periods when three or four stations were operating, 77 network triggers were detected. These triggers were all examined and those which were due to noise or known local earthquakes (of which there were ten) were discarded. For those periods when only one or two stations were working 359 single station triggers on GVIE were investigated. These were almost all noise, often concentrated into short time periods when, presumably, work was being done to the road or viewing platform near the site. Of all of these events only two were earthquakes which were not already in the BGS database. Continuous data for other BGS stations in Scotland were examined at these times and in both cases small signals were observed at some of the nearest sites. Arrival times were picked at the Glendoe stations and any other useful sites and locations made using the standard BGS location software, hypoinverse-2000 (Klein, 2002). The waveforms and locations are included as an appendix.

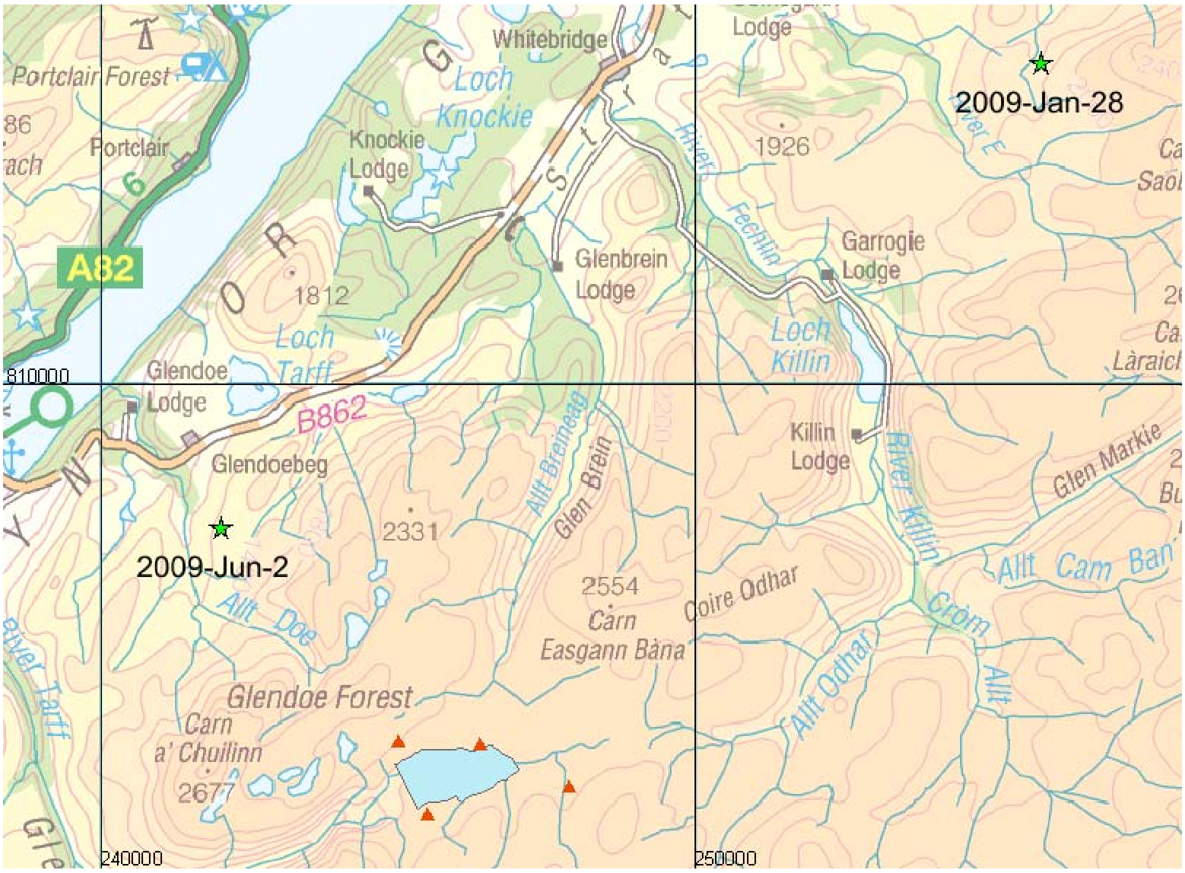

Figure 5: Location of earthquakes detected by the Glendoe network that were not detected by the National network.

The two locations are 16 km northeast of the dam and 6 km to the northwest. The ML1.2 January 2009 event is too far away to have anything to do with the dam and simply shows that the BGS network in Scotland is not yet dense enough to detect events of this size everywhere. The ML1.3 June 2009 event is close to the reservoir but is near the surface and within a kilometre of the cavern under the mountain between the dam and Loch Ness, where the power station is situated. It seems much more likely that this earthquake is associated with stress changes caused by the excavation of the cavern than by the water in the reservoir.

5 Conclusions

An array of four seismometers was installed around the area due for inundation as the reservoir for a new power station at Glendoe. This was done to monitor for possible induced seismicity as the reservoir was impounded or soon afterwards. The network was left in place for over a year after the reservoir was full but no induced seismicity was observed. A detection threshold was estimated by measuring an average maximum noise amplitude at GVIE for October 2008. If the single station trigger at GVIE is assumed to detect any signal of amplitude greater than 5 times this noise amplitude then any earthquake of magnitude 0.5 ML or greater would be detected within 15 km. This is a conservative estimate and at most times smaller events would be detected. The lack of seismicity is probably due to the shallowness of the reservoir, which, despite its size, is only 35 m deep at its deepest point.

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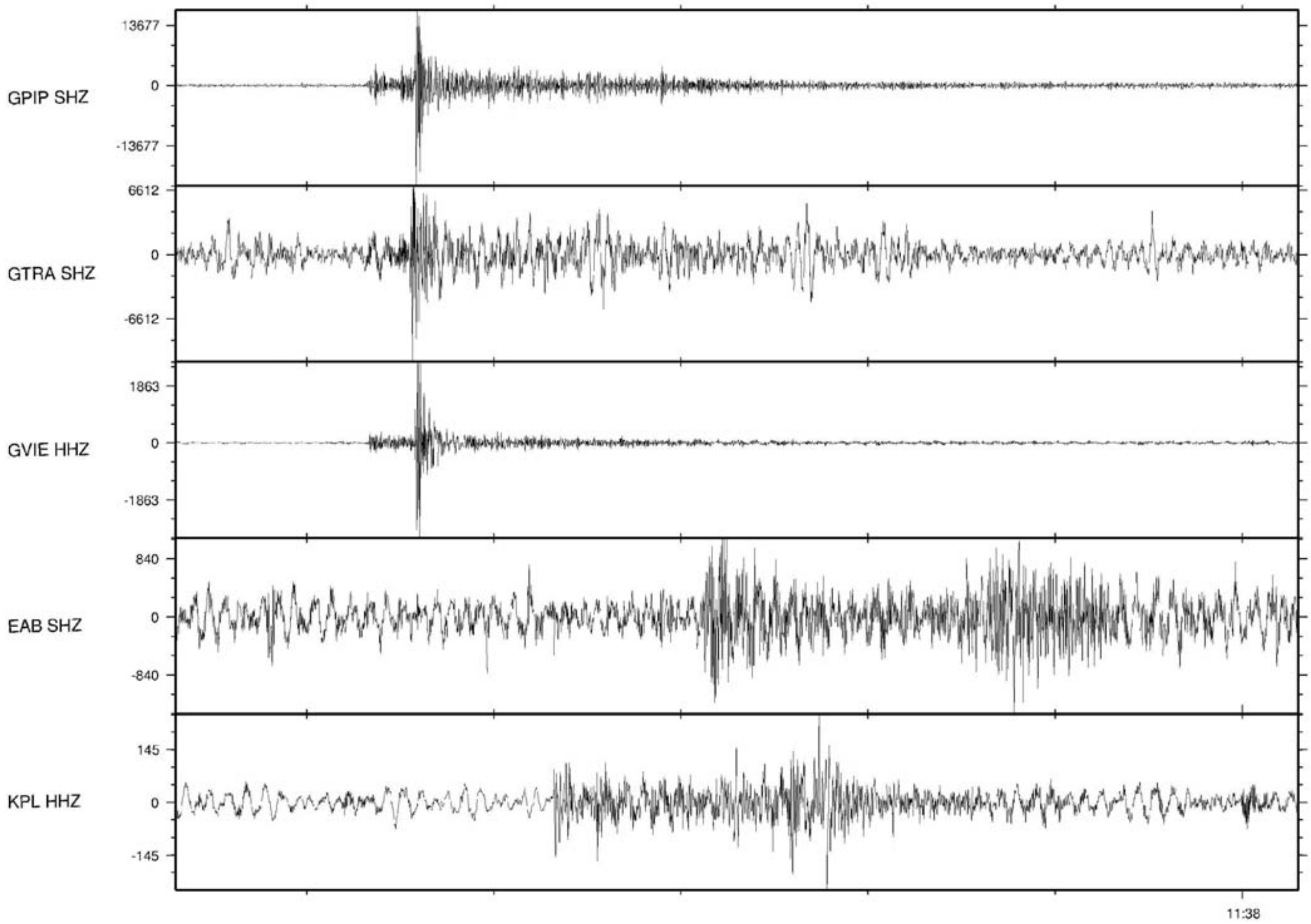
Appendix

Event files in Nordic format (Havskov and Ottemoller, 2005) and trace plots for the earthquakes located by the Glendoe network .

```
 2009  128 1137 10.0 L  57.207  -4.387  1.7  BGS  5 0.1 1.2LBGS                1
 GAP=257        0.16       0.7      2.9  1.7  0.1340E+01  0.4256E+01  0.6839E+00E
 ACTION:UP  09-12-02 16:23 OP:rrl  STATUS:               ID:20090128113700     I
 2009-01-28-1137-00S.BGS___013                                                 6
 STAT SP IPHASW D HRMM SECON CODA AMPLIT PERI AZIMU VELO AIN AR TRES W  DIS CAZ7
 GPIP SZ IP       1137 13.22                              43    0.0610 14.6 211
 GPIP SZ  AMS     1137 15.91                                           14.6 211
 GPIP SZ  AML     1137 15.96       316.3 0.10                          14.6 211
 GTRA SZ IP       1137 13.24                              43    0.0510 14.8 217
 GTRA SZ IS       1137 15.51                              43   -0.0510 14.8 217
 GVIE HZ IP       1137 13.38                              43    0.0210 15.7 222
 GVIE HE IS       1137 15.82                              43   -0.0210 15.7 222
 GVIE HZ  AML     1137 16.19        30.5 0.20                          15.7 222
 KPL  HZ IP       1137 23.23                              38   -0.1210 77.7 281
 KPL  HE IS     D 1137 33.21                              38    0.0710 77.7 281
 KPL  HE  AML     1137 36.08         6.7 0.18                          77.7 281
 EAB  SZ IP     D 1137 28.93                              38   -0.0110  113 178
```



```
2009  6 2 1116 54.24L  57.126  -4.610  0.0  BGS 11 0.3 1.3LBGS                 1
GAP=110        0.92       1.7     2.7  1.9  0.9286E+00  0.1090E+01 -0.1839E+01E
XNEAR  500.0 XFAR 1000.0 SDEP  15.0                                            3
ACTION:UP  09-12-10 13:13 OP:rrl  STATUS:               ID:20090602111640     I
2009-06-02-1116-40S.BGS___024                                                  6
2009-06-02-1115-59S.DRUM__003                                                  6
STAT SP IPHASW D HRMM SECON CODA AMPLIT PERI AZIMU VELO AIN AR TRES W  DIS CAZ7
GVIE HZ EP        1116 55.32                             99    0.0510 4.10 132
GVIE HN ES        1116 55.85                             99   -0.1810 4.10 132
GVIE HN  AML      1116 56.10      493.1 0.34                          4.10 132
GVIE HE  AML      1116 56.32      400.9 0.34                          4.10 132
GTRA SZ EP        1116 55.58                             97    0.0210 5.26 121
GTRA SZ ES        1116 56.22                             97   -0.3110 5.26 121
GTRA SZ  AML      1116 56.42      388.5 0.06                          5.26 121
GQUA SZ EP        1116 55.55                             97   -0.0310 5.35 137
GQUA SZ ES        1116 56.19                             97   -0.3710 5.35 137
GQUA SZ  AML      1116 56.70      326.1 0.19                          5.35 137
MDO  SZ EP        1117  1.43                             43   -0.2710 38.1  23
MDO  SZ ES        1117  6.59                             43   -0.5510 38.1  23
KSB  SZ EP        1117  3.52                             43   -0.1910 50.0 281
KPL  HZ EP        1117  6.59                             38    0.2410 67.3 291
KPL  HN ES        1117 14.82                             38   -0.3810 67.3 291
KPL  HE  AML      1117 19.87        7.8 0.22                          67.3 291
KPL  HN  AML      1117 22.13        8.5 0.50                          67.3 291
MVH1 SZ EP        1117 10.73                             38    0.4210 92.6  16
MCD  SZ EP        1117 11.31                             38    0.4310 96.2  57
MCD  SE ES        1117 22.83                             38   -0.2010 96.2  57
MCD  SN  AML      1117 25.81       20.2 0.28                          96.2  57
MCD  SE  AML      1117 26.09       18.2 0.62                          96.2  57
MME1 SZ EP        1117 11.51                             38   -0.2410  102  77
MME1 SZ ES        1117 24.62                             38    0.0810  102  77
EAB  SZ EP        1117 12.50                             38    0.1510  106 171
EAB  SZ ES        1117 25.62                             38    0.0510  106 171
DRUM HZ EP        1117 17.14                             38    0.8610  131 100
DRUM HN ES        1117 32.81                             38    0.4310  131 100
DRUM HN  AML      1117 36.04       12.8 0.40                           131 100
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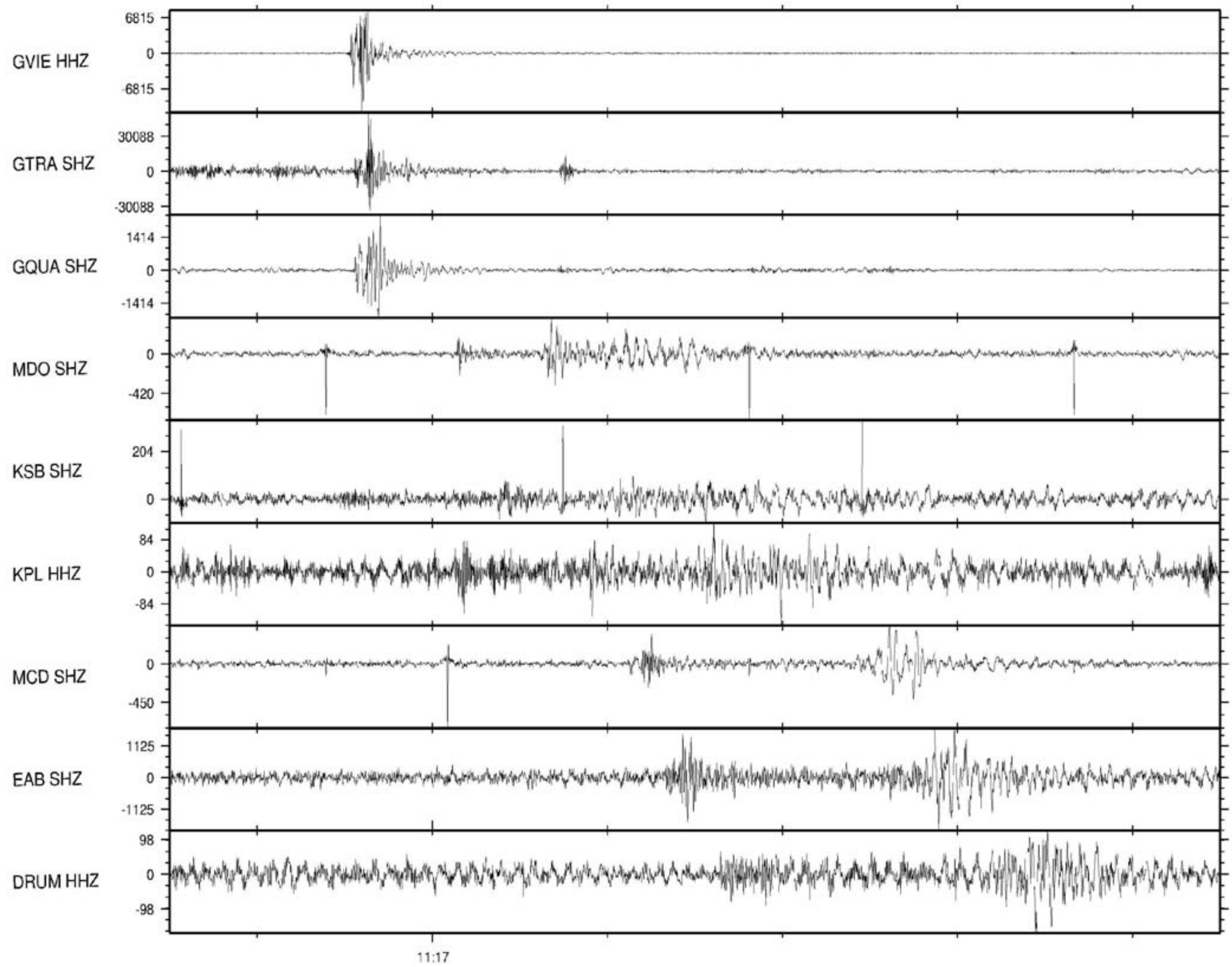

Co-ordinates of the stations deployed around Glendoe resevoir:

GPIP	57° 5.68' N	4° 30.66' W	649m
GQUA	57° 5.42' N	4° 33.00' W	644m
GTRA	57° 6.06' N	4° 32.14' W	618m
GVIE	57° 6.06' N	4° 33.57' W	663m