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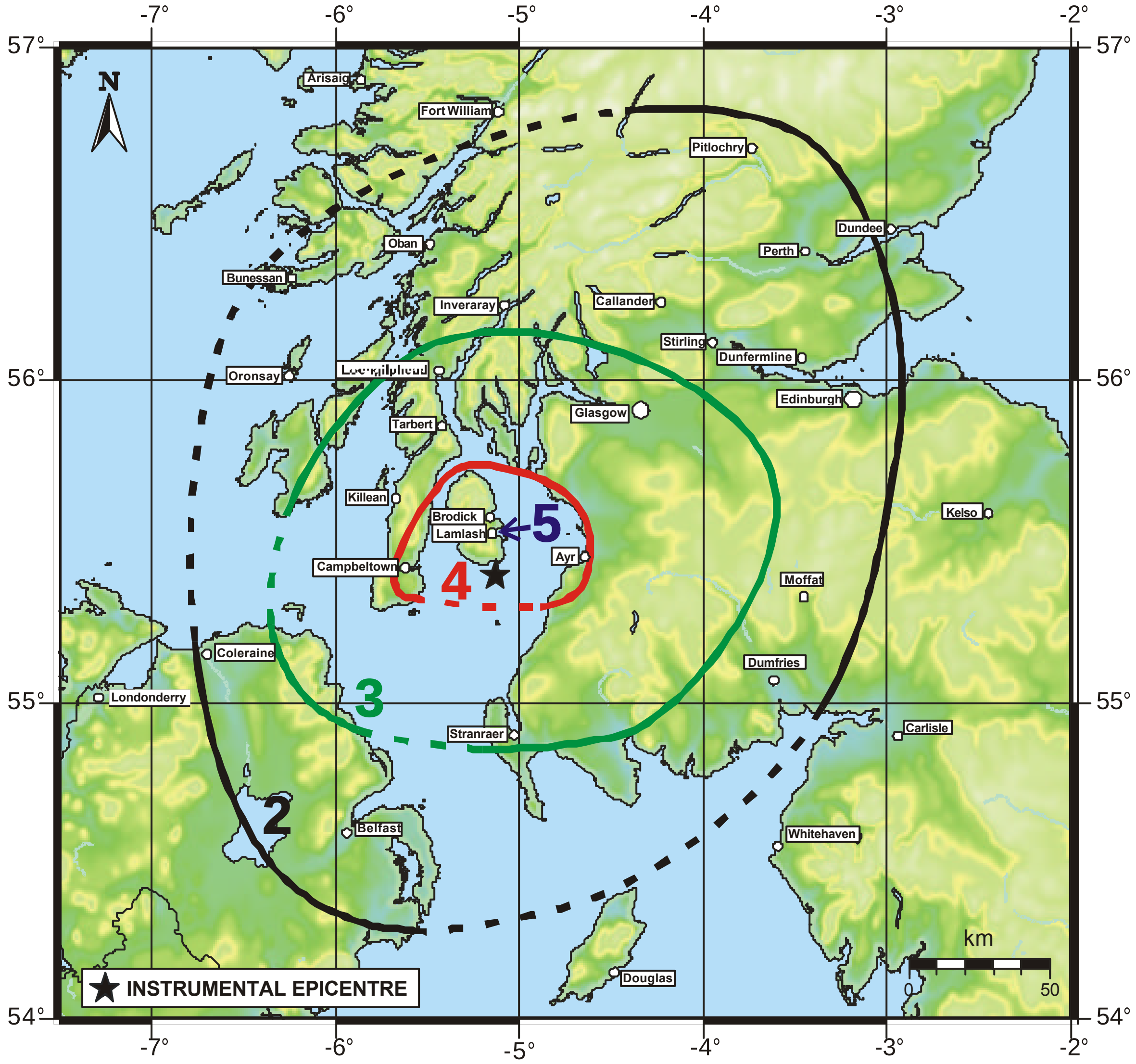
THE 4.0 ML ARRAN EARTHQUAKE OF 4 MARCH 1999



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THE 4.0 ML ARRAN EARTHQUAKE OF 4 MARCH 1999

1. SUMMARY

On 4 March 1999, an earthquake of local magnitude (ML) 4.0 occurred at 00:16 GMT about 3.5 km offshore of the SW corner of the Isle of Arran. The earthquake was located at a depth of 19 km and was felt over an area of about 50,000 km^2 (isoseismal 2 EMS) across western and central Scotland and Northern Ireland. The maximum intensity is reported as 5 on the European Macroseismic Scale (EMS) (Grünthal, 1998) at Lamlash, on the eastern side of the Isle of Arran but in Kilmory, which was closer to the epicentre, it was only felt at 4 EMS. Only two aftershocks were recorded, a 1.6 ML event about 15 minutes after the mainshock, and a 1.1 ML earthquake one week later. The focal mechanism computed for the mainshock is not tightly constrained but indicates dominantly strike-slip faulting with varying degrees of dip slip motion, on either a NW or a NE-striking focal plane. The earthquake occurred in a region where there has been recurrent small magnitude earthquake activity during the 1990's. Earthquake activity peaked in early 1993 (12 events with a maximum magnitude of 1.7 ML) and in the summer of 1996 (14 events with a maximum magnitude of 2.2 ML). This event occurred in a region where no historical earthquakes approaching this size have been located.

2. INTRODUCTION

The Arran earthquake occurred on the southern edge of a roughly wedge-shaped region of active seismicity that is concentrated in central and western Scotland (Figure 1). This region is not only well defined by instrumental earthquakes but also in the historical earthquake record. Historically, Arran itself has not experienced any large local earthquakes, though the largest historical earthquake in Scotland, the 28 November 1880 Argyll event, magnitude 5.2 ML, was located about 90 km to the north (Figure 2), and felt at Lamlash and Brodick Castle on the Isle of Arran (Musson et al., 1984). The 1880 event was felt over an area of about 170,000 km^2 and is thought to have occurred at a depth of about 25 km. Some of the earthquakes that were located in the region near to the 1999 Arran earthquake during the past 10 years also occurred at similar depths to the recent Arran event, but many were much shallower.

Based on the depth distribution of the best located earthquakes in central and western Scotland, most of the seismicity appears to be occurring at depths of 10 km or less. Thus the Arran and also the Argyll earthquake are unusual because their hypocentres are much deeper. All events in central and western Scotland are located with the LOWNET velocity model, developed for the Midland Valley from seismic refraction profiles and used as a general UK velocity model. This velocity model provides reasonable earthquake locations with epicentres for larger events usually being located where they are felt the most. However, the low velocity in the near-surface layer of the velocity model (4 km/sec), appropriate for the near-surface sediments of the Midland Valley, may not be appropriate for regions directly underlain by metamorphic Precambrian rocks, northwest of the Midland Valley. The effect of using this velocity model could be to locate hypocentres at a shallower depth for events in these Precambrian metamorphic terranes, where near-surface velocity is probably between 5.0 and 6.2 km/sec (Hall, 1978; Bamford et al., 1978; Barton, 1992). Conclusions about the relatively great depths of the Arran events are strengthened by this argument.

Seismicity has been occurring in the same general region as the Arran earthquake since 1990 when the first event was detected and located. Before the 1999 event, 32 earthquakes had occurred in three main clusters along a NE-trending lineation. These events are investigated to determine whether the lineation is an artefact of station coverage or whether it could represent a fault plane along which deformation is progressively occurring. No earthquakes were detected prior to the 1990s in this region, and so precursory earthquake activity could possibly serve as a warning for future moderate-sized events in other parts of Scotland if such a pattern was universal. Other similar moderate-sized events are investigated to determine if such precursory activity is commonly observed.

3. EARTHQUAKE LOCATION

BGS seismographs stations throughout Scotland, northern England, Wales and Northern Ireland recorded the Arran earthquake and arrival times mainly from Scottish networks were used along with the LOWNET velocity model to obtain a location using program HYPO71 (Lee and Lahr, 1975). Figure 3 illustrates the geographic distribution of stations used for the location with respect to the epicentre. Arrival times are listed in Table 1. Location output and magnitude calculations are also provided in Tables 2a and 2b. The LOWNET velocity model was derived from the LISPB refraction profile (Bamford et al., 1976; Bamford et al., 1978; Assumpçao and Bamford, 1978) and is most appropriate for the Midland Valley with a low velocity in the near surface (Table 3).

Seismograms recorded on the Borders network for the Arran event are shown in Figure 4. These stations are between 100 and 150 km from the earthquake and are shown because seismograms from closer stations were saturated. The location of the epicentre is offshore, approximately 3.5 km SW of the SW corner of the Isle of Arran, in the same general vicinity of the previously located cluster of earthquakes (Figure 2). The estimated error in epicentral location is 1.9 km. The depth was computed at 19 km ± 2.2 km, indicating a depth range of between 16.8 and 21.2 km. The depth is reasonably well constrained, as the closest station is only 23 km away (GMK). The local magnitude, the average from one orthogonal pair of horizontal components from a standard gain? instrument (BCC) a distance of 135 km away, was 4.0 ML (Table 2b).

The overall location quality of the hypocentral solution obtained using HYPO71 is classified as 'good' B (A*C), with an excellent statistical fit for the data (A), a 'fair' azimuthal distribution of stations (C) and a root mean square error of 0.06 sec. The location errors were calculated relocating the event 50 times using HYPO71 and by randomly perturbing the velocity structure by ± 10% and phase arrivals based on the phase weightings. A one standard deviation (1 sd) change in location is quoted for the epicentral and depth errors, which are estimated to be 1.9 km and 2.2 km respectively. Table 4 lists the details of the output from the error analysis. However, on plotting up the perturbed epicentres, an elliptical shape elongated in the WNW-ESE direction is observed, indicating the location is less stable along this orientation. Epicentral errors (1 sd) parallel and perpendicular to this elliptical trend are estimated to be 1.8 km and 0.3 km, respectively.

Two aftershocks were reported, the first occurring about 15 minutes after the main event, and the second a week later. They were both located very close to the mainshock, the first (1.6 ML) 0.4 km north of the mainshock and the second (1.1 ML) 0.3 km southwest of the mainshock. Since then, there have been four additional earthquakes, the most recent in January 2001, all of which locate within 5 km of the March 1999 mainshock. The largest of these had a magnitude of 2.2 ML and occurred on 24 August 2000. All these events have similar error ellipses to the mainshock, being elongated along the WNW-ESE direction, an artefact of the station distribution for this region.

4. FOCAL MECHANISM

A focal mechanism was computed for the Arran mainshock using the program FOCMEC by Snoke et al. (1984). This program utilises both P-wave first motions, as well as SV/P amplitude ratios. Twenty impulsive P-polarities, of which 10 were dilatational and 10 compressional arrivals and three emergent compressional arrivals were used but no SV/P amplitude ratios, since all stations close enough to be considered for this analysis were saturated. Because of the depth of the earthquake, and its location at or close to one of the boundaries of the layers in the velocity model, most of the polarities plot on the circumference of the focal sphere and therefore cannot constrain the orientation of the NE-striking focal plane.

The resulting focal mechanism (Figure 5) has only one reasonably constrained focal plane, thus the solution represents dominantly strike-slip faulting with varying degrees of dip-slip movement. The better-constrained focal plane is steeply dipping and strikes NW. The poorly constrained focal plane strikes northeast with its dip varying from horizontal to near vertical. The dip is either moderate to the SE or steep to very shallow to the NW. The 'average' P-axis trends N-S, however there is a large scatter and it could lie anywhere within the northern quadrant, from north to northeast with a moderate plunge either to the north or to the south. The 'average' T-axis trends approximately east-west with its plunge varying from horizontal to moderate, again either to the east or to the west.

Further attempts were made to try to improve on the mechanism. However, due to the depth of the event being near a velocity model boundary, almost all unsaturated vertical stations recorded down-going rays and so amplitude ratios could not be used. The only potential station for determining an SV/P ratio was the low-gain station POB, though it had a take-off angle close to 90º. A slight change in depth causes the take-off angle to flip from less than to greater than 90º and so can only be used in some cases. The ratio for POB, however, was difficult to determine with any degree of confidence, as the P-wave was 'nodal' and so very emergent. When the ratio was included it did not significantly improve the focal mechanism, so was not used in the final mechanism. The focal depth was fixed at various depths both above and below the critical boundary layer (at 19 km) in the velocity model to see if this strongly affected the resulting mechanism. The focal mechanisms obtained were not significantly different (Figure 6). However, for fixed depths of 18 km, the NE-trending focal plane is better constrained and close to vertical giving a predominantly strike-slip solution (Figure 6). The focal mechanisms obtained for fixed depths greater of 20 and 22 km were very similar to the one shown in Figure 5 and so provided no significant improvement.

5. MEASURED PEAK GROUND ACCELERATION

The Arran earthquake was recorded on the strong motion instrument installed at Chapelcross (station BCC) some 136 km from the epicentre. The measured accelerations were 1.4 mm/sec^2 on the vertical component, 3.9 mm/sec^2 on the N-S component and 3.6 mm/sec^2 on the E-W component (Figure 7). Ground accelerations were also measured from 64 velocity instruments that were unsaturated and the decay of ground acceleration with distance for this event is illustrated in Figure 8. Both vertical and horizontal accelerations are shown along with predicted horizontal accelerations for a surface-wave magnitude (M_S) 4.0 event, using empirical attenuation relations currently used for UK seismic hazard analyses (Principia, 1988; Ambraseys and Bommer, 1991; Dahle et al, 1990). The peak ground accelerations for the Arran event are much lower than those predicted for the distances shown. This mismatch between predicted and actual peak accelerations has been observed for other moderate-sized UK earthquakes (Marrow, 1992). However, it must be noted that, in the figure, the predicted peak ground accelerations are for 4.0 M_S, equivalent to 4.4 ML, given the relationship between M_S and ML of Marrow (1992). The empirical attenuation relationships were developed from recorded events of M_S = 4.0 from both Europe and California and so may not be appropriate for the UK. Additionally, the attenuation of peak ground accelerations for small events probably differs from that for events large enough to cause significant damage to structures, due to the difference in both in the frequency content of the signal and the duration of high accelerations.

6. GEOLOGICAL AND STRUCTURAL SETTING

The mountainous island of Arran lies on the northern margin of the Midland Valley. This graben is fault-bounded by the Highland Boundary Fault in the north and the Southern Upland Fault in the south. Outcrops of Palaeozoic and Mesozoic rocks occur mainly in the south and east of the island. The Tertiary Arran Granite and the Central igneous complex dominate the north and central parts of the island, respectively. The main Arran Granite to the north is surrounded by a 'halo' of structurally oversteepened Dalradian metasediments. Intrusion of the main Arran Granite was followed by the emplacement of NW-striking Tertiary dyke swarms.

The epicentre of the Arran event was located in the SW Arran trough, in close proximity to the Plateau Fault [follow this up with Derek Ritchie] (Figure 9). The NE-trending Plateau Fault forms the SE margin of the Arran Trough half-graben, and represents a normal fault with downthrow towards the NW. Lower Devonian continental red beds comprise the footwall block whereas Lower Devonian, Upper Devonian and Permo-Triassic fluviatile and lacustrine sedimentary rocks form the hangingwall block (McLean and Deegan 1978; BGS 1985). Seismic survey evidence suggests that the fault is large, with a displacement of 2.5 km at the top of the Lower Devonian level (McLean and Deegan 1978) although, unfortunately, it provides little information regarding the dip or style (e.g. planar or listric) of the fault plane. The Plateau Fault dies out towards the NE of the SW Arran Trough, where its' displacement is probably taken up by the en echelon Dusk Water Fault [follow this up with Derek Ritchie - where is it?] (Figure 9). One of the two planes of the focal mechanism is consistent with the NE strike of the Plateau Fault; whereas there are no nearby major faults with orientations similar to that of the alternative NW-striking plane of the focal mechanism. Within the Midland Valley as a whole, major NW trending normal faults are far less prevalent than NE or E-trending normal faults (Cameron and Stephenson, 1985). However, it should be noted that the Brodick Bay and South of Bute faults form fairly significant NW structures between Arran and the north Ayrshire coast (Figure 9).

Within the SW Arran Trough, the Triassic succession at rockhead appears to be folded (Figure 9). If this folding is significant and not merely the product of sea-bed erosion, it could suggest that there has been a syn- or post-Triassic episode of crustal shortening, with inversion of the SW Arran Trough. Within the eastern Midland Valley of Scotland, Upper Carboniferous-Lower Permian folds are thought to be formed by reactivation (with a reverse sense of movement) of former Devonian-Lower Carboniferous extensional faults, during an earlier phase of crustal shortening (Rippon et al 1996). The present day direction of the maximum compressional stress acting on the UK is orthogonal to the Plateau Fault. It is conceivable that reactivation in a reverse or strike-slip sense of movement of the parent Plateau Fault could be responsible for the recent Arran earthquake.

It should also be noted that the NNW-trending Ailsa Craig Line [follow this up with Derek Ritchie] within the eastern part of the SW Arran Trough occurs close to the epicentral area (Figure 9). This feature is well defined on potential field data (gravity and magnetics), cutting the Plateau Fault and linking the Paleogene Arran Central Complex to the north with the Ailsa Craig granite in the south (McLean and Deegan 1978). Geophysical modelling of the Ailsa Craig Line suggests that the complexes are linked by a linear mass of dense material; probably a basic dyke. This dyke-like feature was responsible for feeding the complexes, possibly utilising a pre-existing fault plane as a convenient path for the upward migration of magma. The possibility exists that the Ailsa Craig Line may have been responsible for the generation of the Arran earthquake and aftershock, though the orientation of the focal planes determined from the focal mechanism are not consistent with this theory.

7. INSTRUMENTAL SEISMICITY

Instrumental monitoring of Scotland since about 1970 reveals a roughly wedge-shaped region of seismicity extending south from Kintail covering central and western Scotland (Figure 1). The 1999 Arran earthquake occurred towards the SW corner of this active region. The same geographic distribution of events is also observed in the historical record (see Section 10). The Arran events define part of the southeastern edge of this active region, with an aseismic region to the south as far as the Southern Uplands, to the east as far as the central Midland Valley, and to the west into Ireland. Three events have been located just to the east of the Isle of Arran along the same general trend as the Arran events and could be occurring along the same overall fault trend. These occurred in 1975, 1985 and 1998, the first two of which may have poor locations due to poor azimuthal coverage, with stations only to the east of the events. The 1975 event, of magnitude 2.5 ML, was reported as felt on Arran as well as the mainland. The felt reports agree with the instrumental epicentre to the east of the island (unpublished BGS archive material). Some diffuse seismicity can be observed along the length of the Kintyre peninsula, just west of the Isle of Arran with activity increasing northwards of both Arran and Kintyre. Only one event above 2.0 ML has been located onshore of Arran, in the southeast corner in 1993 and so the Isle of Arran itself, appears to be relatively aseismic. Earthquake activity near to the Arran event is discussed in more detail in the next section.

8. EARTHQUAKE ACTIVITY NEAR ARRAN

A total of 32 earthquakes occurred during the 1990s in the same region as the Arran mainshock and aftershocks. These events, along with 4 events post-1999, form a NE-striking alignment about 17 km long (Figure 2), with the mainshock at the northern end. There are three distinct clusters of events along this alignment with the southern and central clusters being active during 1993 and 1996. The most recent events occurred in the northern cluster.

[anything more recent than what's here?]

The first event to occur in this region was located in 1990 followed by an another in 1992. In 1993, 12 events occurred, the largest with a magnitude of 1.7 ML, followed by 1½ years of quiescence. Activity began again in early 1995, with four events, and culminated in 1996 with 14 events, the largest with a magnitude of 2.2 ML. No more events were located in this region until the 4 March 1999, 4.0 ML event. Only two aftershocks were reported with magnitudes of 1.6 and 1.1 ML the first occurring within 15 minutes and the second within a week of the mainshock, indicating that most of the stress was released during the main event. Four additional earthquakes have occurred since, three in 2000 and one in 2001, all of which locate in the northern cluster.

The 1993 events occurred in both the central and southern clusters, whereas most of the 1996 events were located in the southern cluster. The depths of the 1993 events are between 5 and 18 km, but in contrast, the 1996 events all locate below 15 km with the majority around 7 to 8 km. Overall, the depth of events appears to shallow from 19 km in the north to about 3.5 km in the south (Figure 10). The NE alignment of the three clusters was investigated to see if it was an artefact of station coverage, or whether it might reveal the orientation of a causative fault. The lineation is parallel to one of the focal planes in the focal mechanism, however, it is the one whose dip is poorly constrained (See Section 4 and Figure 5). A cross-section perpendicular to the epicentral trend (B-B') indicates an approximately vertical distribution of hypocentres (Figure 10). A cross-section parallel to the epicentral trend (A-A') reveals the increase in hypocentral depth towards the north (Figure 10)

In the error analysis of the mainshock (Section 3), the 50 perturbed epicentres plot along an ellipse elongated along the west-northwest direction about 0.3 km wide and 1.8 km long. The major axis of the error ellipse is perpendicular to the lineation of the three clusters. If station control were optimal, a more spherical distribution would be expected, with the degree of lineation increasing as azimuthal coverage decreases. There is therefore less control along the WNW-ESE direction as shown in the perturbed epicentres. This observation gives us some reassurance that the NE-SW epicentral trend observed in the earthquake epicentres may be real. In 3 dimensions, the perturbed epicentres for the mainshock appear to locate between about 15 and 22 km depth, with a slight trade-off between depth and distance from the SE.

The 38 events comprising the three Arran clusters were re-examined, but no significant improvement in the location could be obtained despite reviewing all arrival times. In summary, magnitudes of these events are between 0.8 to 2.2 ML and the focal depths between 3.5 to 17.9 km, with an average of 10.1 km (Table 5). Locations are 'fair' on average with 11 having 'good' (B) quality locations, 17 with 'fair' (C) quality location and 4 with 'poor' (D) location quality. A list of all these events and their location statistics are shown in Table 5 along with the mainshock, aftershocks and more recent events in the region. Epicentral errors were computed using the perturbation analysis for all events and the estimated depth errors vary from 2.2 to 6.9 km and horizontal errors from 1.6 to 20.0 km. The events occurred within a zone about 17 km long, along a NE trend.

The perturbed epicentres from the error analysis of all events were found to form elliptical distributions around each of the epicentres. Error ellipses were drawn through these groups of perturbed epicentres to summarise the errors in the location estimates (Figure 11). To determine the error ellipses the best-fit line was found which minimised the absolute deviation (Press et al., 1992, p. 703). The standard deviations of epicentres perpendicular to and parallel to this best-fit line were determined and represent the lengths of major and minor axes of the "error ellipses". These "error ellipses" are not true confidence ellipses because they don't necessarily contain 68% of the perturbed epicentres, but provide a good general indication of the epicentral errors.

A plot of the error ellipses reveals a distinct geographic pattern (Figure 11). Most of the events in the central and northern clusters have error ellipses elongated along a WNW direction, similar to that of the mainshock (Figures 11c and 11d). The error ellipses for the northern group are the smallest indicating that these earthquakes have the best locations, with the majority occurring at depths of around 18 km (Figure 10). The orientations of the major axes of the error ellipses indicate that the events have stable locations in the NNE direction, but less stable along the WNW direction. These events have between 4 and 14 arrival time picks, with an average of 8 or 9, most of which include Paisley network data, to the NE of the epicentres (Table 5). The error ellipses of events in both the northern and the central cluster do not overlap, indicating that these clusters are in fact separate and distinct. Most of the events in the central cluster locate at depths between 12 and 16 km, with 4 events at depths less than 9 km. The two clusters are 6.5 km apart with events in the central cluster having slightly shallower hypocentres.

In contrast, all events in the southern cluster (Figure 11b) have large error ellipses mostly elongated to the NNE, the same direction as the overall alignment of epicentres. Most of the error ellipses encompass the central cluster and some encompass the northern cluster too. These poorly constrained epicentres can be explained by their having only 4 or 5 arrival time picks, from stations GMK, GCL and GAL, two of which are along the same azimuth to the SW, and the other is to the SE (Table 5; Figure 3). The P- and S-wave arrival-time picks at the 3-component station GAL appear to strongly control the exact location. All these events have been located at shallow depths (<10 km) and lack data from the Paisley network. One of these events (16 June 1996 at 07:13) was investigated to see how fixing the hypocentre at various depths affected the location and rms errors. The rms error increased with increasing depth above the computed depth of 7.6 km, from 0.04 to 0.21 sec, for a depth of 20 km. The location moved about 7 km to the NNE of the original location for a depth of 20 km (Figure 12). There is a trade-off between depth, location and origin time for all the events in the southern group due to the large azimuthal gap. If the depths are fixed at about 17 km (the depth of the deepest events in the central cluster), then the epicentres locate just within the central cluster region. This suggests that these events probably occurred in the central cluster, and their locations further to the SW result from a lack of Paisley data. In contrast the locations of events from the two other clusters with fixed depths of between 5 and 20 km, show limited westward movement as depth increases.

To test this theory further, events from the central and northern clusters were relocated without using Paisley data. It was found that the epicentres moved SW to within the region around the southern cluster. Therefore it is possible that the events within the southern cluster could have occurred either within the central or the northern cluster if Paisley data were available [Glenn - why no Paisley data?].

To try to distinguish to which group these events belong, S-P times were determined for all events at the vertical station GCL. The station is situated along the same approximate azimuth as the epicentral trend, and therefore the maximum difference in S-P times between clusters is observed. Picking S wave arrivals is difficult on a vertical instrument, so the S-P times only provide a rough estimate of the distance. The central and northern clusters are about 6 or 7 km apart and should produce an S-P time difference between 0.5 and 0.8 seconds. The results (Table 5) are illustrated in Figure 13, and verify that there are only two major clusters of events, one with an S-P time between 7.0 and 7.5 sec, and one with between 7.7 and 8.1 sec. A few scattered epicentres have S-P times for station GCL of greater than 8.1 sec and these events locate further to the north. All events from the southern cluster have similar S-P times to those of the central cluster and so this confirms that these epicentres are just poorly located and probably occurred in the central cluster rather than the northern one.

9. PRECURSORY ACTIVITY FOR LARGER INSTRUMENTAL EVENTS IN SCOTLAND

To determine whether occurrence of small earthquakes in a region might provide a warning of moderate-sized ones such as the Arran event, other similar-sized instrumental (post-1970) events in Scotland were investigated for similar activity. Earthquakes of 3.5 ML and larger in Scotland in this period are the 29 August 1972, Dunoon earthquake (3.5 ML), the Kintail swarm (1974-1978) with maximum magnitude of 4.4 ML (10 August 1974 event), the 1 December 1985 Mallaig earthquake (3.7 ML), the 29 September 1986 Oban earthquake (4.1ML) and the 3 May 1998 Jura event (3.5 ML). Each is discussed below in terms of activity prior to and after the event.

The 1972 Dunoon (or Lochgilphead) earthquake of magnitude 3.5 ML was preceded by an event by about 5 months of no reported magnitude, and located 4.5 km to the south. However, instrumental monitoring of local earthquakes in Scotland only began in 1969, and so there are not significant instrumental recordings from before this event to definitively say one way or another.

The 1974-1978 Kintail earthquakes, with magnitudes between 1.5 and 4.4 ML, occurred as part of a swarm sequence over a period of 4 years, beginning on 9 April 1974. The largest event was the eighth earthquake in the sequence and was preceded by events with magnitudes between 3.0 and 4.1 ML. No prior activity is listed in the instrumental catalogue before the 9 April event. The Kintail region has experienced some activity in the 1990's, though mostly just single events or pairs of events with magnitudes less than 1.0 ML.

The 1 December1985 Mallaig earthquake (3.7 ML) was preceded by six small events, which occurred between September 1984 and January 1985, the largest having a magnitude of 2.2 ML. There was no immediate aftershock activity, though three events occurred 3 to 4 months later, followed by two about one year later, all of which were small (magnitudes less than 1.7 ML). A few events of magnitude less than or equal to 2.2 ML occurred in Loch Nevis between 1989 and 1991, a distance of 1-2 km away from the Mallaig event. In 1993, earthquake activity was again detected in the vicinity of the Mallaig event and a series of 21 events of magnitude between 0.1 and 2.7 ML were located between 4 and 24 September. Two small precursory events to this sequence (0.7 ML and –0.2 ML) occurred in April and August of 1993. All these events align along a NW-SE trend in the mouth of Loch Nevis. Since 1993, only isolated events or pairs of events have occurred, totalling 7 events, with magnitudes ≤ 2.3 ML.

The 1986 Oban earthquake (4.1 ML), was preceded by two events the day before, both of which were felt (magnitudes of 1.7 and 1.0 ML). Two events also occurred in 1981 and two in the same region in the 1970s. Four aftershocks occurred within 2 hours, the largest with a magnitude of 1.2 ML, all of which were located between 4 and 9 km from the mainshock. Several events have occurred since in the 1990s on the Isle of Mull with magnitudes less than 2.1 ML, some 9-10 km to the southwest of the 1986 Oban event.

The most recent moderate-sized event, the 1998 Jura earthquake (3.5 ML) was preceded by 4 events between 1979 and 1994 all with magnitudes between 1.4 and 2.7 ML. The offshore location may contribute to the lack of small events located in this region. This area has a large station gap and the nearest station, PMS, on the Paisley network, is 85 km to the east. No aftershocks were reported for this event either.

In summary, clustered precursory earthquake activity of the type observed before the Arran earthquake has not been seen elsewhere in the instrumental record for Scotland. This could be a function of the location of moderate-sized events with respect to the slowly developing network over the past 30 years, several of the larger events occurring in the 1970's. The only earthquakes for which there might be potential precursory activity are the 1985 Mallaig and 1998 Jura earthquakes. There have been no other moderate-sized events with which to test this further, though swarms and clusters of events are common in Scotland. Instrumental seismicity in Scotland typically occurs as single events evenly distributed geographically and temporally throughout the roughly wedge-shaped region, with swarm and/or clustered activity in certain areas. Therefore it is difficult to distinguish between the general background of small events and swarms, and events that might be precursory. In conclusion, similar-sized events to the 4.0 ML Arran event could occur anywhere within the wedge-shaped region in central and western Scotland. However, most of the larger instrumental and historical events in Scotland have occurred towards the western side of the wedge (Figure 1), except for historical events reported at Inverness and at Comrie.

Based on the premise that clustered activity could potentially indicate the sites of future 3.5+ ML events, the following regions are noted as having clustered/swarm smaller earthquake activity in the instrumental record:

- Ullapool in 1987 and 1988 along a WNW trend (maximum magnitude of 2.5 ML);
- Crianlarich in 1986 and 1990 (magnitudes less 2.0 ML) along a WNW trend;
- Glenalmond in 1971 with magnitude less than or equal to 2.6 ML along a NW trend;
- Comrie (also historically active) 1986-1987 with magnitude less than 2.3 ML along a NNW trend;
- Blackford and Ochil Hills, with 1979, 1997 and 2000 being the most active years, with no distinct alignment and with magnitudes less than 3.2 ML.

10. HISTORICAL SEISMICITY

There are no known historical records of events occurring on or close to the Isle of Arran, though some larger regional earthquakes have been felt on the island. The nearest earthquake to the recent events historically is the 15 July 1889 Kintyre earthquake, with a magnitude of 3.2 ML, which was felt in NW Arran (Figure 2). This event was located, using macroseismic methods, 37 km to the NNW on the Kintyre peninsula (Musson, 1994; Principia, 1982). Also, a similar-sized event (4.1 ML) to the Arran earthquake occurred between Colintrave and Lochgilphead on 27 January 1927, a distance of about 60 km to the north (Musson et al., 1984). This event was felt with a maximum intensity of 5 and was thought to have occurred at a shallow depth. The largest known earthquake in Scotland occurred about 90 km north of the Arran event (Figure 2) on 28 November 1880, in Argyll (Musson, 1994). This event was widely felt (over an area of about 170,000 km^2), including Lamlash and Brodick Castle on the Isle of Arran (Musson, 1989). No intensities greater than 5 were assigned for this event and this has been interpreted as resulting from a deep source or complex geology.

11. MACROSEISMIC STUDY

Following the occurrence of the Arran earthquake, a questionnaire survey of the affected area was launched by BGS. Questionnaires were published in the newspapers listed in Table 6. The questionnaire and the methodology used to process the data are described in detail in Musson and Henni (1999). All intensities are in the European Macroseismic Scale (EMS-98) and described in detail in Grünthal (1998).

About 1000 completed questionnaires were received from a wide area of southern Scotland, with a few from Northern Ireland. These were grouped by place (village, town, suburb) yielding about 230 locations. From many of these, only one or two questionnaires were received; usually insufficient for assessing intensity values; these were coded as “F” for felt or as intensity 1 (not felt) if the report was negative. A synopsis of the data is presented in Table 8, the assigned intensity values are shown in Figure 14 and interpreted regions of equal intensity (isoseismal lines) in Figure 15.

The highest intensity of 5 was observed at Lamlash, on the eastern side of the Isle of Arran (not the place closest to the epicentre). Thirty-one questionnaires received from this village, which agree on the strength of the effects observed. In two cases people ran outside with fright. There were a number of cases of objects such as ornaments, pictures or toys falling or being displaced, but in a few cases heavy objects were also said to have been displaced, including two washing machines, a cooker, a microwave and a sofa. The earthquake was perceptible out of doors but no damage was reported.

At Whiting Bay, south of Lamlash, the intensity may have approached 5, but the evidence is not so strong. A total of 21 questionnaires were received with one report of someone running out of their house, but only one report of any objects being moved. However, there were two reports of slight damage – in one case plaster dust and small pieces of plaster fell from the junction between the ceiling of a room and the walls. In a second report, small exterior cracks in the rear wall of a cottage were attributed to the earthquake. An intensity of 4-5 (4 or 5) has been assigned to Whiting Bay.

The place nearest the epicentre of the earthquake is Kilmory; where very slight damage was also reported in the form of a hairline crack above the kitchen door in a farmhouse. Another observer reported that the frame of an inside door on the ground floor had been affected, so that the door no longer closed so well. Apart from these two details, the effects were not remarkable, and the intensity has been assessed as 4.

In the rest of Arran the intensity was generally 4 and it is evident that many people slept through the earthquake. At Lochranza, at the north end of the island, it was estimated that 70-80% of sleepers were not awakened. However, for those awake, the earthquake was perceptible on the ground floor of houses as much as on upper floors.

On the mainland, intensity 4 was also experienced along the coast in the Ayr-Ardrossan area. 88 questionnaires were received from Ayr, which indicate that those who were awake felt the event, but that most people slept through it. There were a few reports of objects falling or being shifted. Two reports could be construed as damage: in one case five tiles fell off a kitchen wall; in another, cracks in a ceiling were attributed to the earthquake.

The situation was similar in Prestwick; again, only a few people were woken but many who were awake felt the earthquake and there were some cases of small objects being upset, pictures swinging, and so on. Intensity 4 was also observed at Campbelltown and other places in the south-east part of the Kintyre peninsula.

Away from the coast, the intensity of the shock dropped rapidly, and for most of south-west Scotland was only 3 – this includes the Glasgow conurbation, from which relatively few replies were received considering the high population. It was commonly reported that the earthquake was only perceptible on upper floors.

In Northern Ireland the earthquake was not felt as strongly as was first supposed from reports received immediately after the earthquake. Only in one village (Cushendun, on the Antrim coast) did the intensity reach 3. The earthquake was hardly perceptible at all (intensity 2) in Belfast. The furthest observations were from Rasharkin (Antrim) in the west, and Ballynahinch (Down) to the south.

In Scotland the most distant extremes of perception were Dumfries in the south-east, Innerleithen (Borders) and Leven (Fife) in the east, Grandtully (Perthshire) in the north, and Oban to the north-west. The shock was felt (albeit weakly) throughout Islay in the west.

One interesting character of this earthquake is the relatively high number of reports of effects on objects, even when the intensity was not especially high. This is particularly the case with hanging objects swinging, which is an effect normally not encountered much in British macroseismics, but commonly reported for this earthquake. A notable case in point is the town of Kilwinning (near Ardrossan). Out of fifteen replies received from here, six reported that hanging objects (lights, pictures, a mobile) were set in motion, and five reported that small objects fell. Yet, most of the reports were from upper floors, few were wakened or frightened, and it is not convincing that the intensity was any higher than 4. A possible explanation is that this earthquake had a higher low frequency content than is normal with British earthquakes, which, being small, are usually richest in high frequencies. It was notable, for example, during the Musselburgh mining-induced events in 1996 (Walker, 1997)) that even when people perceived the shocks as frighteningly strong, domestic items were completely unaffected.

The expected radii (column 3 of Table 7) are those expected from applying standard UK intensity attenuation to the instrumental parameters. The expected values are very close to the actual values determined; though the area for intensity 3 is a little larger. Also, comparing the plotted isoseismals with circles of the expected radius, the isoseismals extend slightly more to the east than expected. The epicentre based on the macroseismic data would place the earthquake on the east coast of Arran, close to Lamlash, with an error of about 15 km in a north-easterly direction.

The macroseismic depth for the earthquake, using the method described in Musson (1996), is 18 km, in excellent agreement with the instrumental depth of 19 km. The macroseismic magnitude, calculated from isoseismal 3, is 4.2 ML and when calculated from isoseismal 4 is 3.9 ML. These two values bracket the instrumental value of 4.0 ML, so are in agreement.

The higher ground shaking at Lamlash with respect to other locations on the Isle of Arran may result from site conditions, earthquake radiation pattern or, possibly, directivity of the fault rupture. Recently, very high accelerations of 0.50g and 0.34g were recorded in the Napa Valley, California, at a distance of 10 and 17 km away from an earthquake of magnitude 5.2 ML (EERI, 2000). The high accelerations occurred to the southeast of the epicentre, where the greatest damage was reported, and are thought to be a result of rupture directivity (USGS, 2000) and amplification of soft sediments along the Napa river.

Since the focal mechanism for the Arran event is poorly constrained, it is hard to infer whether the radiation pattern could explain the strong shaking to the north of the epicentre. If slip occurred northwards along the NE-striking focal plane, then the effect of directivity might have increased the ground shaking at Lamlash and Brodick. Lamlash, along with other towns in southern Arran (Whiting

Bay, Kildonan, Lagg, Blackwaterfoot, Tormore and Brodick) all sit on Permian or Permo-Triassic sediments, mostly sandstones, so there appears to be no difference in underlying bedrock between these sites. There are some differences in the drift deposits that overlie the bedrock, with Lamlash, Lagg, Blackwaterfoot, Tormore and Brodick all situated on raised beach deposits. In contrast, Whiting Bay is situated at the edge of a patch of boulder clay/morainic drift and Kildonan has no drift. These differences could also have affected the reported level of shaking at the different locations.

12. DISCUSSION

The Arran earthquake of 4 March 1999 (4.0 ML) was the largest event to occur in the region since the 4.1 ML Colintrave earthquake of 27 January 1927, which occurred about 60 km to the north. The Arran earthquake occurred in a region where no significant historical earthquakes have been reported, and where only recent small magnitude earthquake activity has occurred. The event was located at a depth of 19 km, about 3.5 km off the southwest corner of the Isle of Arran. It was felt over a large area (about 55,000 km^2 at 2 EMS) but not at particularly high intensities, which is commonly observed for deep hypocentres. The macroseismic epicentre, depth and magnitude agree well with those calculated instrumentally and so we believe the depth to be reasonable despite being close to a velocity boundary of the velocity model. Additionally, many of the other smaller events within the clustered activity near the main event also locate at similar depths.

The depths of the best-located Arran events (B quality) are greater than the average for the best-located earthquakes in Scotland. However, the depths of events in western part of Scotland are not particularly well constrained due to the poor station coverage, and often the closest station can be over 50 km from the event. The use of the LOWNET velocity model, which has a low velocity in the near surface, might not be appropriate for most of the seismically active part of central and western Scotland, which is underlain by Precambrian metamorphic rocks with higher near-surface velocities. Therefore, many events may be overly shallow, though the difference in velocities would probably only produce a difference of about 1-2 km in depth in the upper crust. Any such effect strengthens the conclusion that the Arran events are significantly deeper than seismicity elsewhere in Scotland, generally by a factor or two.

Previous earthquake activity (maximum of 2.2 ML) occurred during the early to mid-1990s, but was seismically quiescent for a few years prior to this event. Earthquake activity was found to concentrate in two clusters, about 6.5 km apart. The 1999 event and all subsequent events locate within the northern cluster, the other cluster being more active in 1993 and 1996. Originally, the earthquake epicentres located into three distinct clusters that aligned along a NE-trend; however, events in the southern cluster appear to be mislocated due to a lack of Paisley network stations, northeast of the epicentres. These events were mostly located using arrival times from just three stations, to the southeast and southwest of the region (GCL, GMK and GAL). Error ellipses for these events, calculated from randomly perturbed input parameters, showed elongation in the NE-direction, along the strike of the three clusters. Thus, the station distribution strongly affected these locations and they could easily have occurred in either of the other two clusters. A similar situation was observed for the 1988 Hay-On-Wye, Worcester swarm whose epicentres aligned along a NNE direction, but more detailed analysis revealed this to be an artefact of station distribution and so only an apparent effect (Ritchie and Wright, 1991). For the Arran clusters, S-P arrival times were measured at station GCL, 60 km SW along strike from the three original clusters, and this revealed only two distinct groups of epicentres, with the southern and central cluster events having about the same S-P times. Therefore, we believe that the events located in the southern cluster actually should be located further north, in the central cluster. Major axes of the error ellipses of events from the two other clusters are smaller, and the major axes are oriented WNW, rather than NNE. The error ellipses do not overlap between these two clusters, implying that these events have fairly good locations and that there are two distinct clusters of epicentres. The two clusters are separated by 6.5 km horizontally and about 3 km vertically.

Precursory earthquake activity such as observed for the Arran event, has not been recorded for other similar-sized earthquakes in the instrumental record (last 30 years). A few events do have some precursory events, but not as much as observed for the Arran event. Precursory activity, therefore, cannot be used as a definitive predictor for the location of future moderate earthquakes. Swarm and clustered activity are fairly common in Scotland in both the instrumental and historical records. It is not known whether these areas will continue to be active at a small magnitude level or whether larger events might occur in the future at these locations. Larger historical and instrumental events in central and western Scotland have generally occurred towards the western edge of the active wedge-shaped region. Exceptions to this are for historical events reported at Comrie and Inverness. Future earthquakes will probably follow this same pattern of occurrence.

The seismic activity in this region is indicative of contemporary movement along a line of weakness in the Arran area, possibly the Plateau Fault. However, a lack of location control in the WNW direction and a trade-off with depth and origin time would preclude a positive correlation of the earthquakes with this fault. The depth of these events is also well below that of current seismic imaging in the region. Access to the BP AMOCO commercial seismic reflection data, to the south of Arran, could potentially help resolve the structure of the Plateau fault plane at depth. This could then assist in confirming whether it is possible for this fault plane to intersect at depth with the calculated focal depth of the Arran earthquake.

The focal mechanism for the Arran event, though poorly constrained, indicates strike-slip faulting with varying degrees of dip-slip motion (oblique normal to oblique reverse) depending on the amount and direction of dip of the NE-striking focal plane. The possible T-axes are approximately EW but with varying strike and plunge, and are generally consistent with the horizontal minimum stress direction determined from bore-hole breakouts and measured for other UK earthquakes (Brian Baptie, BGS, unpublished report). The possible P-axes plunge moderately, either to the north or to the south or SW. The direction of the P-axes is consistent with the regional compression of the European plate due to ridge-push at the Mid-Atlantic ridge from the north and NW and the collision of Africa into Europe from the south. Other authors (Muir-Wood, 2000) have suggested that the earthquakes in Scotland and England result from post-glacial rebound after the last major ice age, whose maximum occurred over 10,000 years BP. This theory is based on the geographic pattern of earthquake occurrence in Scotland being similar to that of maximum ice thickness in the last ice age. Additionally, the pattern of seismic and aseismic regions, appears to match that expected from the superposition of the post-glacial relaxation on the regional NW-SE-directed compressive stresses. This combination predicts particular styles of faulting to dominate in different quadrants around the rebound region. Since the Arran earthquake's focal mechanism cannot be fully constrained using first motions, we cannot definitively agree or disagree with this model, since either oblique-normal, oblique-reverse or strike-slip faulting are all possible. However, the depth of this event might suggest the source to be of tectonic rather than rebound origin.

13. ACKNOWLEDGEMENTS

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TABLE 1

INPUT DATA FOR THE HYPO71 LOCATION PROGRAM

```
HEAD
RESET TEST( 3)=  0.500

  GMK 5520.75N  535.60W 164
  PMS 5550.75N  444.71W 351
  PGB 5548.69N  429.02W 199
  GCL 55 4.70N  6 7.58W 278
  GAL 5451.98N  442.68W 117
  PCA 5542.04N  415.30W 302
  POB 5550.75N  425.79W  34
  PCO 5559.28N  4 6.01W 267
  GCD 5451.78N  356.42W 184
  BWH 5510.55N  339.29W 269
  BNA 5457.95N  337.45W  28
  ESK 5518.99N  312.31W 261
  BHH 55 5.59N  313.09W 216
  BCC 55 0.92N  313.21W 138
  GMM 5414.26N  556.99W 155
  EDI 5555.40N  311.25W 125
  WIM 54 8.85N  440.43W 386
  EBL 5546.34N  3 2.67W 436
  BBO 5444.20N  314.78W 209
  ESY 5555.05N  236.85W 337
  WCB 5322.69N  432.80W 139
  WME 5323.81N  418.19W 129
  WLF 5317.36N  423.80W  58
  YRC 5315.05N  434.52W  22
  YRE 5258.87N  425.52W 193
  SBD 5254.33N  315.51W 489

  4.000  0.000
  5.900  2.520
  6.450  7.550
  7.000 18.870
  8.000 34.150

  10.  70. 100. 1.73    4    1                        1 1111
GMK IPU  990304001656.80
PMS IPD  9903040017 1.82
PGB IPU  9903040017 2.93       10.90ES 1
GCL IPU1 9903040017 2.88
GAL IPD1 9903040017 3.23       11.38ES 1
PCA IPU  9903040017 3.56
POB EP 3 9903040017 3.60
PCO EP 2 9903040017 7.46
GCD IPU  9903040017 8.74
BWH IPU1 9903040017 8.84
BNA EPU1 990304001710.46
ESK EPU1 990304001712.29       27.54ES 2
BHH EPU1 990304001713.43
BCC EP 4 990304001714.08
GMM IPD1 990304001713.13
EDI IPU4 990304001713.88
WIM IPD4 990304001714.04
EBL IPU4 990304001714.22
BBO IPU4 990304001714.68
ESY IPU4 990304001718.10
WCB IPD4 990304001724.80
WME IPD4 990304001724.84
WLF IPD4 990304001726.08
YRC IPD4 990304001726.43
YRE IPD4 990304001730.43
SBD IPD4 990304001734.20
                 10
```

TABLE 2a

OUTPUT FILE FROM HYPO71 LOCATION PROGRAM

```
Date         : 04/03/99
Origin time :  0:16:51.75
Epicentre   : 55-23.82 deg N   5-14.48 deg W   (  55.3970 /   -5.2413 )
Grid ref    :   194.768 East /  616.233 North
Depth       :   19.01 kms
Quality     : B A*C

              NO DM GAP M  RMS  ERH  ERZ
Statistics  : 10 23 136 1 0.06  0.4  1.2
Magnitude   :  4.0 ML     (from  2 readings)
Magnitude   : No valid coda readings
```

STN	DIST	AZM	AIN	P-RES	P-WT	S-RES	S-WT
GMK	23.0	256	118	0.00	1.72		
PMS	59.0	32	90	-0.01	0.69		
PGB	66.4	46	90	0.03	0.69	-0.13	0.52
GCL	66.6	238	90	-0.04	1.29		
GAL	68.1	150	90	0.10	1.29	-0.06	1.29
PCA	70.9	62	90	0.02	3.34		
POB	71.5	46	90	-0.03	0.16		
PCO	97.4	47	90	0.14	0.03		
GCD	102.1	126	90	0.74	0.00		
BWH	103.7	104	90	0.61	0.00		
BNA	113.6	115	90	0.82	0.00		
ESK	129.3	94	90	0.41	0.00	0.96	0.00
BHH	133.2	105	90	0.99	0.00		
BCC	135.5	108	90	1.31	0.00		
GMM	136.9	199	90	0.17	0.00		
EDI	141.8	66	90	0.21	0.00		
WIM	143.8	165	90	0.09	0.00		
EBL	144.7	73	90	0.14	0.00		
BBO	147.1	120	61	0.28	0.00		
ESY	175.1	71	61	0.20	0.00		
WCB	229.2	169	61	0.14	0.00		
WME	230.8	165	61	-0.03	0.00		
WLF	241.0	167	61	-0.05	0.00		
YRC	242.8	170	61	0.07	0.00		
YRE	274.1	169	61	0.15	0.00		
SBD	306.0	155	61	-0.07	0.00		

TABLE 2b

INDIVIDUAL MAGNITUDES CALCULATED FOR EACH STATION

STATION	MAGNITUDE
BCC	: 4.0 ML

BCC : 4.0 ML

TABLE 3

DEPTH / CRUSTAL VELOCITY MODEL USED IN THE ARRAN EARTHQUAKE LOCATION

Depth to top of layer (km)	P-wave velocity (km/sec)	Vp/Vs
0.00	4.00	1.73
2.52	5.90	
7.55	6.45	
18.87	7.00	
34.15	8.00	

TABLE 4

ERROR DIAGNOSTICS: 50 PERTURBED HYPOCENTRES

The initial epicentre, using a trial depth of 10.00 km
was 0:16:51.75 194.77 km E, 616.23 km N Depth 19.01 km

Subsequent epicentres.....

Origin time	kmE	kmN	Depth	Epicentre change(km)	Depth change(km)
0:16:52.08	193.78	616.85	18.63	1.17	-0.38
0:16:51.36	195.07	615.64	20.74	0.66	1.73
0:16:51.97	194.13	616.60	19.94	0.74	0.93
0:16:51.75	194.41	616.38	18.48	0.38	-0.53
0:16:51.59	195.20	615.88	20.94	0.55	1.93
0:16:50.82	195.19	615.45	20.02	0.89	1.01
0:16:51.58	195.33	615.76	20.53	0.73	1.52
0:16:51.89	194.34	616.29	17.59	0.43	-1.42
0:16:51.87	194.71	616.44	17.32	0.21	-1.69
0:16:51.58	195.17	616.16	19.52	0.40	0.51
0:16:50.91	190.53	618.23	23.47	4.69	4.46
0:16:52.40	193.22	617.29	22.06	1.87	3.05
0:16:51.75	193.93	616.57	19.49	0.91	0.48
0:16:51.51	198.66	615.11	10.00	4.05	-9.01
0:16:51.88	194.41	616.46	16.30	0.42	-2.71
0:16:51.75	194.43	616.36	17.43	0.37	-1.58
0:16:51.88	194.61	616.32	18.18	0.18	-0.83
0:16:51.55	194.91	615.87	18.57	0.39	-0.44
0:16:52.63	193.56	617.83	13.78	2.00	-5.23
0:16:52.08	193.67	615.80	21.07	1.18	2.06
0:16:51.42	195.39	615.57	20.75	0.91	1.74
0:16:52.07	194.36	616.70	18.56	0.62	-0.45
0:16:51.95	194.18	616.59	16.26	0.69	-2.75
0:16:51.00	200.37	610.57	20.07	7.96	1.06
0:16:51.78	195.71	615.85	17.64	1.02	-1.37
0:16:51.32	195.21	615.34	21.80	1.00	2.79
0:16:52.30	193.77	616.99	15.13	1.25	-3.88
0:16:51.99	193.81	616.74	19.84	1.09	0.83
0:16:51.59	198.76	615.21	10.00	4.12	-9.01
0:16:51.64	194.98	616.04	17.20	0.29	-1.81
0:16:51.85	194.38	616.44	19.05	0.44	0.04
0:16:51.68	193.60	616.79	22.54	1.29	3.53
0:16:52.01	194.11	616.67	17.51	0.79	-1.50
0:16:52.04	194.06	616.53	18.97	0.76	-0.04
0:16:52.04	194.33	616.51	17.90	0.52	-1.11
0:16:51.33	196.93	615.50	12.67	2.29	-6.34
0:16:51.50	194.41	616.25	19.91	0.36	0.90
0:16:51.65	195.02	615.92	19.11	0.40	0.10
0:16:51.48	195.26	615.62	20.89	0.79	1.88
0:16:51.56	194.35	616.18	19.75	0.42	0.74
0:16:51.36	198.97	614.94	10.00	4.39	-9.01
0:16:52.26	193.87	617.09	15.71	1.25	-3.30
0:16:51.42	194.35	615.97	20.01	0.49	1.00
0:16:52.06	194.26	616.68	18.31	0.68	-0.70
0:16:51.79	194.68	616.37	19.01	0.16	0.00
0:16:51.78	194.73	616.20	19.41	0.05	0.40
0:16:51.62	195.53	615.81	19.67	0.87	0.66
0:16:52.15	194.21	616.85	17.07	0.83	-1.94

0:16:52.28	193.60	617.09	17.58	1.45	-1.43
0:16:51.38	195.22	615.51	22.13	0.86	3.12

Epicentre standard deviation =   1.88 km
Depth   standard deviation =   2.18 km

Dy mo year	Hrmn	Secs	East (km)	North (km)	Depth (km)	ML	jitt-esd (km)	jitt-dsd (km)	No. of Arrivals	Dm (km)	Gap	Sqd	Qal	Rms (sec)	Major Axis (m)	Minor Axis (m)	Angle	Paisley data	GCL S-P times (secs)	Cluster
14/03/1990	1803	20.9	196.026	614.875	17.9	1.7	1.90	5.24	7	24	131	A*B	B	0.08	1822	328	103	Y	7.89	N
30/09/1992	1652	46.2	194.785	611.830	8.1	1.2	2.60	4.03	6	23	123	C*C	C	0.16	2486	375	95	Y	6.85	C
06/01/1993	1812	41.4	191.171	610.161	17.9	1.1	2.64	4.86	8	19	120	A*B	B	0.07	2314	929	97	Y	7.58	C
06/01/1993	2141	45.6	193.631	610.918	6.6	1.1	7.54	6.93	8	21	121	A*C	B	0.08	7246	912	105	Y	6.87	C
06/01/1993	2246	57.2	189.062	606.787	13.7	1.0	5.26	4.85	5	18	218	A*D	C	0.02	4331	2873	35	N	7.23	S
06/01/1993	2323	43.2	190.238	605.895	8.5	0.9	7.10	5.75	5	19	217	B*D	C	0.02	4190	3928	60	N	7.12	S
07/01/1993	0016	56.1	190.638	603.164	5.0	0.9	9.19	2.87	6	20	209	D*D	D	0.04	8416	2987	29	N	7.31	S
07/01/1993	0153	45.2	191.792	611.209	14.8	1.0	4.01	4.00	10	20	123	A*B	B	0.12	3411	1247	121	Y	7.36	C
07/01/1993	1559	11.7	191.860	610.853	11.8	1.7	2.43	5.17	13	20	122	B*B	B	0.17	1686	722	93	Y	7.35	C
07/01/1993	1700	45.5	191.227	613.130	15.2	1.5	2.36	2.69	12	19	130	B*B	B	0.23	2254	582	113	Y	7.49	C
07/01/1993	1706	18.4	190.882	608.317	13.7	0.9	6.00	4.50	5	19	227	B*D	C	0.07	5065	3109	30	N	7.67	C
07/01/1993	1844	35.8	189.752	605.491	13.1	1.2	3.98	3.59	6	19	215	A*D	C	0.03	3913	1777	20	N	7.28	S
13/06/1993	0522	55.3	194.191	616.781	17.0	1.3	6.35	4.18	14	59	278	C*D	D	0.38	5285	752	83	Y		N
08/08/1993	1159	19.2	204.115	623.422	7.6	1.6	1.74	5.19	19	34	141	A*C	B	0.09	1681	331	116	Y	8.88	
09/01/1995	0538	53.8	192.457	610.044	12.6	1.1	5.98	4.89	7	20	146	B*C	C	0.08	3095	1841	107	Y	7.24	C
31/03/1995	1734	48.4	192.762	608.878	7.5	0.8	5.01	2.21	5	61	263	D*D	D	0.08	4904	2434	20	N	7.33	C
04/04/1995	0141	40.5	192.250	609.924	7.6	1.1	2.38	3.63	8	61	149	C*D	D	0.19	2198	657	91	Y	7.02	C
31/10/1995	0303	56.1	197.580	617.475	13.3	1.6	2.12	3.85	8	26	133	C*B	C	0.20	3887	591	103	Y	8.08	N
29/05/1996	0519	57.6	190.559	605.731	6.8	0.9	5.38	3.18	4	19	217	A*D	C	0.02	4676	1979	41	N	7.45	S
14/06/1996	1727	19.9	195.112	608.843	14.2	1.3	4.03	6.04	5	23	128	A*D	C	0.03	3769	999	98	Y	7.45	C
15/06/1996	2153	37.2	190.745	604.292	5.8	0.8	9.16	2.49	4	20	213	A*D	C	0.05	4292	3319	47	N	7.44	S
16/06/1996	0713	16.1	191.577	606.426	7.6	1.0	11.88	4.05	4	20	221	A*D	C	0.04	10407	2623	39	N	7.43	S
23/06/1996	1847	41.6	191.204	603.249	3.8	0.9	20.02	2.92	4	21	210	A*D	C	0.04	19053	2656	18	N	7.51	S
26/06/1996	0152	42.1	192.979	609.667	13.9	2.2	1.55	3.60	10	21	117	A*B	B	0.04	1483	218	98	Y	7.53	C
26/06/1996	0256	12.5	191.221	605.849	7.7	1.1	13.32	3.16	4	20	219	A*D	C	0.03	11373	3300	30	N	7.45	S
27/06/1996	1115	36.4	191.479	606.152	7.0	0.8	13.18	2.91	4	20	220	A*D	C	0.02	11152	3047	31	N	7.39	S
29/06/1996	0140	55.0	191.094	605.390	5.2	1.0	9.31	3.96	4	20	217	A*D	C	0.06	6768	3619	29	N	7.27	S
28/07/1996	1442	13.3	194.602	610.185	14.1	1.4	2.02	6.62	6	22	132	A*B	B	0.03	1707	713	102	Y	7.39	C
04/08/1996	0525	4.9	193.648	609.933	13.0	1.3	2.39	4.77	8	22	118	B*B	B	0.09	2097	850	105	Y	7.38	C
11/08/1996	0430	54.6	189.577	605.592	7.6	0.9	5.96	3.46	4	18	215	A*D	C	0.05	5423	1950	33	N	7.44	S
12/08/1996	0835	33.8	191.055	605.466	7.6	1.0	13.06	2.90	4	20	217	A*D	C	0.07	10901	3231	33	N	7.44	S
29/12/1996	0435	50.6	187.925	603.851	3.5	0.9	9.57	3.11	4	18	206	A*D	C	0.05	8922	2705	27	N	7.45	S
04/03/1999	0016	51.8	194.768	616.233	19.0	4.0	1.88	2.18	10	23	136	A*C	B	0.06	1819	320	115	Y	7.82	N
04/03/1999	0030	57.0	194.431	616.045	18.4	1.6	4.54	4.23	8	23	136	A*C	B	0.06	4384	630	106	Y	7.99	N
11/03/1999	1406	29.1	194.877	616.544	15.6	1.1	1.62	4.85	8	23	137	B*C	C	0.16	1444	290	115	Y	7.74	N
25/06/2000	0431	17.0	195.142	614.971	14.8	0.9	1.75	4.52	6	23	132	B*B	B	0.08	1245	654	127	Y	7.84	N
13/08/2000	2233	56.2	199.072	617.892	10.0	1.0	2.04	3.78	6	28	135	C*C	C	0.15	1820	522	123	Y	8.46	N
24/08/2000	0749	21.2	194.615	616.129	18.9	2.2	2.24	5.65	8	23	136	B*C	C	0.09	1993	272	107	Y	8.47	N
30/01/2001	2010	6.5	196.884	614.668	8.1	1.3	2.31	5.30	8	25	129	C*C	C	0.1	2139	498	115	Y		N

TABLE 5 - CATALOGUE OF ARRAN EARTHQUAKES

TABLE 6

NEWSPAPERS AND PUBLICATION DATES FOR QUESTIONNAIRES

NEWSPAPER	PUBLICATION DATE
Arran Banner (weekly)	Wed./Thurs. w/e 14/03/1999
The Herald (Saturday)	06/03/1999
The Scotsman (Saturday)	06/03/1999
Scotland on Sunday (with above)	07/03/1999
Oban Times Group (weekly); Oban Times, Cambletown Courier, Argyllshire Advertiser	Wed./Thurs. w/e 14/03/1999
Ayrshire Post Group (weekly); Ayrshire Post, Kilmarnock Standard, Irvine Herald, North Ayrshire World	Wed./Thurs. w/e 14/03/1999
The Belfast Telegraph (Saturday)	06/03/1999

TABLE 7

INTENSITIES, ACTUAL FELT AREAS AND EXPECTED VERSUS EQUIVALENT RADII

Intensity	Area	Equivalent radius	Expected radius
4	2600	29	26
3	18700	77	62
2	55000	132	127

Macroseismic magnitude	4.2 (A_3), 3.9 (A_4) (instrumental 4.0 ML)
Macroseismic depth (km)	18 (instrumental 19 km)
Maximum intensity (I_{max})	5 EMS (Lamlash)

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Aberfoyle	251.000	701.000	F	-4.401	56.178	1	1	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0
Achahuish	178.000	677.000	F	-5.555	55.935	2	2	0	2	1	1	0	0	1	0	1	0	1	0	0	0	1	1	1	1	0	1	1	0	0
Achnamara	170.000	675.000	F	-5.681	55.913	2	2	0	2	0	2	0	0	2	0	2	0	0	0	0	0	2	0	0	2	0	0	2	0	0
Alloway - Doonfoot	234.000	618.000	4	-4.624	55.428	28	25	3	23	0	20	3	5	24	2	21	1	4	11	10	3	11	16	10	17	2	0	27	0	0
Ardbeg	248.000	667.000	F	-4.430	55.872	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0
Ardmay	229.000	703.000	F	-4.756	56.189	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0
Ardrossan	223.000	642.000	3	-4.813	55.639	8	7	1	6	0	6	0	2	5	0	5	0	2	3	1	0	5	2	1	4	0	0	6	0	0
Auchencloigh	253.000	632.000	F	-4.331	55.559	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Auchentiber	236.000	647.000	F	-4.609	55.689	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1	0	0	1	0	1	0	0	1	0	0
Auchinleck - Cumnock	256.000	621.000	3	-4.278	55.462	7	7	0	5	0	5	0	1	7	1	6	0	0	1	2	0	4	2	1	5	1	1	5	0	0
Ayr	234.000	622.000	4	-4.626	55.464	88	83	5	76	4	68	4	12	66	19	44	3	15	8	28	6	26	45	26	38	9	7	72	1	0
Balfron	254.000	688.000	F	-4.345	56.063	2	2	0	2	0	2	0	0	2	0	2	0	0	1	1	1	1	1	0	1	0	0	2	0	0
Ballantrae	208.000	582.000	F	-5.009	55.095	2	2	0	2	0	2	0	0	2	0	2	0	0	1	0	0	1	1	2	0	0	0	2	1	0
Balloch	240.000	682.000	F	-4.566	56.004	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Ballygally	152.000	563.000	F	-5.869	54.900	1	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0
Ballynahinch	146.000	507.000	F	-5.913	54.395	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Bangor	165.000	535.000	F	-5.644	54.655	1	1	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0
Barbreck	184.000	707.000	1	-5.483	56.207	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Barrhead	250.000	659.000	3	-4.393	55.801	9	9	0	7	1	6	0	1	5	0	4	1	2	3	3	2	5	3	1	4	0	1	8	0	0
Bathgate	298.000	669.000	F	-3.632	55.903	1	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0
Bearsden	254.000	672.000	3	-4.337	55.919	4	4	0	4	1	2	1	0	1	0	1	0	1	0	0	0	2	1	1	3	1	0	4	0	0
Beith	235.000	654.000	F	-4.629	55.751	1	1	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	0	0
Belfast	148.000	528.000	2	-5.901	54.584	4	4	0	3	0	3	0	0	2	0	2	0	2	0	1	0	2	2	1	2	0	0	4	0	0
Biggar	304.000	638.000	F	-3.525	55.626	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Bishopbriggs	261.000	670.000	F	-4.224	55.903	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Bishopton	243.000	671.000	F	-4.512	55.906	2	2	0	2	0	2	0	0	1	0	1	0	1	0	1	0	1	1	1	1	0	0	2	0	0
Blackwaterfoot	190.000	628.000	4	-5.325	55.501	8	5	3	5	0	4	1	3	3	0	3	0	4	4	1	0	3	2	2	2	0	0	5	0	0
Blanefield	256.000	679.000	F	-4.308	55.982	2	2	0	2	0	1	1	0	1	0	1	0	1	0	0	0	0	2	0	2	0	0	2	0	0
Bo'ness	300.000	681.000	F	-3.604	56.012	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	1	0	1	0	0	1	0	0
Bonnybridge	281.000	680.000	F	-3.908	55.998	2	1	1	1	0	1	0	1	1	0	1	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Bowmore	131.000	659.000	F	-6.287	55.749	2	2	0	1	0	1	0	1	0	0	0	0	2	0	0	0	0	2	0	1	0	0	1	0	0
Breakachy by Campbeltown	167.000	627.000	F	-5.688	55.481	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	1	0	0
Bridge of Allan	279.000	697.000	2	-3.948	56.150	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Bridge of Weir	239.000	665.000	3-4	-4.572	55.851	10	10	0	7	1	6	0	2	8	0	8	0	2	4	1	0	4	3	5	2	2	0	9	1	0
Bridgend	133.000	662.000	F	-6.258	55.777	1	1	0	0	0	0	0	1	1	0	1	0	0	1	1	0	0	1	0	0	0	0	1	0	0
Bridgeton	261.000	664.000	F	-4.220	55.849	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	0	1	1	0	1	0	0
Brodick	201.000	636.000	4	-5.157	55.577	29	28	1	25	1	23	1	3	19	2	17	0	7	18	11	8	14	9	7	14	1	1	24	0	0
Buchlyvie	264.000	694.000	F	-4.188	56.119	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0
Cambuslang	265.000	660.000	F	-4.155	55.814	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Campbeltown	170.000	620.000	4	-5.635	55.420	34	30	4	25	3	21	1	7	23	9	14	0	7	15	10	8	12	12	8	15	5	3	26	0	0
Cardonald	253.000	664.000	3	-4.348	55.847	12	12	0	10	1	8	1	2	8	0	7	1	0	4	1	1	4	8	4	5	1	1	11	1	0
Cardross	235.000	678.000	F	-4.644	55.967	2	2	0	2	0	2	0	0	1	0	1	0	1	0	0	0	1	1	0	2	0	0	2	0	0
Carluke	285.000	651.000	F	-3.832	55.739	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
Carradale	181.000	638.000	4	-5.476	55.586	14	14	0	12	3	9	0	2	14	5	9	0	0	10	7	8	9	4	6	2	2	1	13	0	0
Carryduff	148.000	520.000	1	-5.894	54.512	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Carse	174.000	661.000	F	-5.605	55.789	1	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	1	1	0	1	0	0
Castle Douglas	277.000	562.000	1	-3.920	54.937	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Cathcart	258.000	661.000	3	-4.267	55.821	11	11	0	9	1	7	1	2	7	0	7	0	4	1	6	0	0	9	1	9	0	0	11	1	0
Catrine/Mauchline	252.000	626.000	3	-4.344	55.505	5	5	0	5	0	5	0	0	5	2	3	0	0	2	3	0	2	3	2	2	0	0	5	0	0
Chiskan, Southend	173.000	609.000	F	-5.579	55.323	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Clachan	177.000	656.000	3-4	-5.553	55.746	4	3	1	3	1	2	0	1	3	1	2	0	1	3	1	0	2	1	3	1	2	1	2	0	0
Clarkston	257.000	657.000	3	-4.281	55.785	6	5	1	4	0	4	0	0	1	0	1	0	4	0	0	0	1	4	1	3	0	0	5	0	0
Conlig	163.000	532.000	F	-5.672	54.627	1	1	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	1	0	1	0	1	0	1	0
Corryiach Farm	170.000	630.000	F	-5.643	55.509	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	0	1	0	1	0	0	0	1	1	0
Corsock	276.000	576.000	F	-3.942	55.063	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0
Coylton - Belston	240.000	620.000	3	-4.530	55.448	5	5	0	5	0	3	2	0	5	0	5	0	0	2	2	1	0	5	2	3	0	0	5	0	0
Craigie	242.000	632.000	F	-4.505	55.556	2	2	0	2	0	2	0	0	2	0	2	0	0	1	1	0	2	0	1	0	0	0	2	0	0
Craobh Haven	180.000	708.000	F	-5.548	56.214	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0
Crawfordjohn	288.000	624.000	F	-3.773	55.497	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Creetown	248.000	559.000	F	-4.371	54.902	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	0	1	0	1	0	0	0	1	0	0
Crossford	283.000	647.000	3	-3.862	55.702	3	3	0	3	0	3	0	0	3	0	3	0	0	3	0	0	1	2	0	2	0	0	3	0	0
Crosshouse	239.000	638.000	F	-4.556	55.609	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Cumbernauld	276.000	675.000	F	-3.986	55.952	1	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0
Cushendun	136.000	587.000	3	-6.140	55.107	7	6	1	1	0	0	1	6	5	0	5	0	2	4	0	1	0	5	0	5	0	0	5	0	0
Dailly	227.000	601.000	F	-4.724	55.273	2	2	0	2	0	1	1	0	1	0	1	0	1	0	0	0	0	2	0	2	0	0	2	0	0
Dalavich	197.000	713.000	F	-5.278	56.266	1	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0	0	1	0	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Dalbeattie	283.000	561.000	F	-3.826	54.930	1	1	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
Dalry	260.000	581.000	F	-4.195	55.104	2	2	0	2	0	2	0	0	1	0	1	0	1	1	0	0	1	1	0	2	0	0	2	0	0
Dalry	229.000	649.000	3	-4.722	55.704	3	2	1	1	0	1	0	2	0	0	0	0	3	0	1	0	1	1	2	0	1	1	1	0	0
Dalrymple	236.000	614.000	F	-4.590	55.392	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0
Darvel	256.000	637.000	F	-4.286	55.605	2	2	0	1	0	1	0	1	0	0	0	0	2	0	1	0	0	2	1	1	0	0	2	0	0
Dougarie	188.000	637.000	F	-5.364	55.580	1	1	0	1	0	1	0	0	1	1	0	0	0	0	1	0	0	1	0	1	0	0	1	0	0
Douglas	283.000	631.000	F	-3.855	55.559	2	2	0	1	0	1	0	0	0	0	0	0	1	1	0	0	1	0	2	0	0	1	1	0	0
Dreghorn	235.000	638.000	F	-4.620	55.608	2	2	0	2	0	2	0	0	1	0	1	0	1	0	0	0	0	2	1	1	0	1	1	0	0
Drymen	247.000	688.000	F	-4.458	56.060	3	3	0	2	0	1	1	1	2	0	2	0	1	1	0	0	0	2	0	2	0	0	2	0	0
Dumbarton	239.000	675.000	2	-4.578	55.941	2	2	0	2	0	2	0	0	2	0	2	0	0	0	0	0	0	2	0	2	0	0	2	0	0
Dumfries	298.000	576.000	3	-3.597	55.068	7	7	0	4	0	3	1	2	6	0	5	1	0	4	3	0	3	3	0	0	0	0	7	0	0
Dundonald	236.000	634.000	F	-4.601	55.572	3	2	1	2	0	1	1	1	1	1	0	0	1	2	0	0	0	0	2	0	0	0	3	0	0
Dunlop	240.000	649.000	3	-4.547	55.708	3	3	0	2	0	2	0	1	2	0	2	0	1	0	1	0	0	2	0	3	0	0	3	0	0
Dunoon	217.000	677.000	1	-4.931	55.951	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Dunscore	287.000	584.000	F	-3.773	55.137	1	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0
Dunure	225.000	615.000	F	-4.764	55.398	3	3	0	3	0	3	0	0	3	1	1	1	0	1	0	0	2	1	0	2	0	1	2	2	0
Eaglesham	257.000	652.000	F	-4.278	55.740	2	2	0	2	0	2	0	0	1	0	1	0	1	1	1	0	0	2	1	1	0	1	1	0	0
East Carrine, Southend	165.000	611.000	F	-5.706	55.337	1	1	0	1	1	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	1	0	1	1	0
East Kilbride	263.000	654.000	3	-4.184	55.760	16	10	6	9	0	9	0	6	6	1	5	0	7	2	0	0	3	6	1	7	0	1	9	0	0
Elderslie	245.000	663.000	F	-4.475	55.835	2	1	1	1	1	0	0	1	0	0	0	0	2	0	0	0	0	1	0	2	0	0	2	0	0
Erskine	247.000	670.000	F	-4.447	55.899	3	3	0	3	0	3	0	0	1	0	1	0	2	1	1	0	0	3	0	3	0	1	2	0	0
Firkin Farm	234.000	700.000	F	-4.674	56.164	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0
Galston	249.000	637.000	F	-4.397	55.603	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0
Garelochhead	224.000	691.000	F	-4.828	56.079	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Garrowhill	267.000	664.000	F	-4.125	55.851	2	2	0	2	0	2	0	0	1	0	1	0	1	1	1	0	0	2	0	2	1	0	2	0	0
Gartocharn	242.000	686.000	F	-4.537	56.041	2	2	0	2	0	2	0	0	2	0	2	0	0	1	0	0	1	1	0	1	0	0	0	0	0
Girvan	218.000	597.000	3-4	-4.862	55.234	7	7	0	6	0	6	0	1	3	1	2	0	2	4	3	1	3	2	2	4	0	1	5	1	0
Glenluce	220.000	557.000	F	-4.806	54.875	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	0	0	1	0	1	0	0	1	0	0
Gourock	222.000	677.000	F	-4.851	55.953	2	2	0	1	0	1	0	1	1	0	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0
Govanhill	258.000	663.000	F	-4.268	55.839	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	1	0	0	0	1	0	0
Grandtully	290.000	752.000	F	-3.794	56.647	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Greenisland	150.000	540.000	F	-5.880	54.693	1	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0
Hailes, Edinburgh	321.000	670.000	2	-3.264	55.917	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Hamilton	272.000	655.000	1	-4.041	55.771	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
Helen's Bay	159.000	536.000	F	-5.737	54.661	1	1	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	1	0	0
Helensburgh	230.000	683.000	3	-4.727	56.010	3	3	0	2	1	1	0	1	3	0	3	0	0	0	1	0	0	3	0	3	0	2	1	0	0
Hollybush	240.000	616.000	F	-4.528	55.412	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Houston (& Crosslee)	241.000	666.000	3	-4.541	55.861	6	6	0	3	0	2	1	3	4	0	4	0	1	2	2	2	0	4	2	3	0	1	4	0	0
Hyndford Bridge	291.000	641.000	F	-3.732	55.650	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Innerleithen	333.000	636.000	F	-3.064	55.613	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Inverkip	221.000	672.000	F	-4.864	55.908	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Inverneil	184.000	682.000	F	-5.463	55.982	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Irvine	232.000	639.000	3	-4.668	55.616	15	14	1	12	1	10	1	3	8	1	7	0	6	5	4	2	0	9	3	6	0	1	11	1	0
Isle of Seil, by Oban	186.000	730.000	2	-5.470	56.414	1	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1	0	0
Isle of Whithorn	247.000	536.000	F	-4.374	54.696	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0
Johnstone	243.000	663.000	3	-4.507	55.835	10	10	0	7	0	7	0	3	5	1	3	1	3	3	4	1	1	9	2	6	1	2	7	0	0
Kames	197.000	671.000	F	-5.247	55.889	1	1	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0
Kelloholm	273.000	611.000	F	-4.005	55.376	2	2	0	2	0	2	0	0	0	0	0	0	2	0	1	0	0	2	0	2	0	0	2	0	0
Kelvinbridge	257.000	669.000	F	-4.287	55.893	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	1	1	0	0	1	0	0	1	0	0
Kelvinside	257.000	668.000	3	-4.286	55.884	6	4	2	4	0	4	0	2	1	0	1	0	5	0	1	0	0	4	0	4	1	0	4	0	0
Kilbarchan	240.000	663.000	F	-4.555	55.834	3	2	1	2	0	2	0	1	1	0	1	0	2	0	0	0	0	2	0	2	0	0	2	0	0
Kilchiaran, Islay	121.000	660.000	F	-6.447	55.753	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Kilchousland	174.000	621.000	F	-5.573	55.431	2	2	0	2	0	2	0	0	2	2	0	0	0	0	0	0	1	0	1	0	0	0	2	0	0
Kildonan	203.000	621.000	4	-5.115	55.443	10	10	0	9	2	7	0	1	9	4	5	0	1	9	5	3	3	5	3	2	1	0	8	0	0
Killearn	252.000	685.000	3	-4.376	56.035	4	4	0	3	0	3	0	1	3	0	3	0	0	4	0	0	0	3	0	4	0	0	4	0	0
Kilmacolm	236.000	669.000	F	-4.622	55.886	2	2	0	1	0	0	1	0	2	0	2	0	0	0	0	0	0	2	0	2	0	0	2	0	0
Kilmarnock	243.000	638.000	3	-4.493	55.610	23	19	4	15	0	14	1	8	15	2	13	0	7	9	6	3	4	11	5	10	3	1	16	1	0
Kilmaurs - Rowallan	242.000	642.000	3	-4.511	55.646	4	4	0	2	0	2	0	2	3	1	2	0	1	0	2	0	1	3	2	2	0	0	4	0	0
Kilmelford	184.000	713.000	F	-5.488	56.260	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1	0	0	1	0	1	0	0	1	0	0
Kilmory - Sliddery	195.000	622.000	4	-5.242	55.449	6	6	0	6	0	6	0	0	6	4	2	0	0	0	2	3	1	2	3	1	0	0	6	1	0
Kilwinning	230.000	643.000	4-5	-4.702	55.651	15	15	0	14	1	13	0	1	12	0	12	0	0	5	5	3	9	3	9	3	6	5	8	0	0
Kings Cross	205.000	628.000	4	-5.088	55.507	4	4	0	4	2	2	0	0	4	1	3	0	0	2	3	1	2	2	1	1	1	0	4	0	0
Kirkcudbright	268.000	551.000	F	-4.056	54.836	2	2	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Kirkintilloch	266.000	673.000	3	-4.145	55.931	4	3	1	2	0	2	0	2	1	0	1	0	2	2	2	1	1	2	2	1	0	0	3	0	0
Kirkmichael	234.000	608.000	F	-4.618	55.338	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Kirkmuirhill	279.000	643.000	F	-3.924	55.665	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Kirkoswald	224.000	607.000	F	-4.775	55.325	2	2	0	2	0	2	0	0	1	0	1	0	1	2	0	0	0	1	0	1	0	0	2	0	0
Kirkpatrick Durham	279.000	570.000	F	-3.892	55.010	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	0	0
Kirkwood	239.000	647.000	F	-4.562	55.690	1	1	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0	1	0	0
Knightswood	252.000	669.000	F	-4.367	55.891	2	1	1	1	0	1	0	1	1	0	1	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Knock and Maize, Portpatrick	200.000	559.000	F	-5.118	54.886	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Lagg Croft	264.000	685.000	F	-4.183	56.039	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Lamlash	202.000	630.000	5	-5.137	55.524	31	31	0	28	2	24	2	3	26	15	10	1	2	19	13	7	14	14	8	15	5	9	21	0	0
Lanark	289.000	644.000	3	-3.765	55.677	7	7	0	4	0	4	0	3	3	0	2	1	2	0	1	0	1	5	1	5	0	1	5	0	0
Langbank	238.000	672.000	F	-4.592	55.914	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Laphroaig - Lagavulin	139.000	645.000	F	-6.147	55.628	2	2	0	2	2	0	0	0	2	0	2	0	0	0	1	0	0	1	1	0	0	0	1	0	0
Largs	220.000	659.000	3-4	-4.871	55.791	9	8	1	7	0	5	2	2	6	1	5	0	2	3	0	1	3	2	3	2	0	1	6	0	0
Larkhall	276.000	651.000	F	-3.975	55.737	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Leven	338.000	700.000	F	-2.999	56.189	1	1	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0	1	0	0
Liberton, Edinburgh	327.000	669.000	1	-3.168	55.909	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Locharbriggs	299.000	579.000	F	-3.583	55.095	2	2	0	2	0	2	0	0	2	0	2	0	0	1	1	0	1	0	1	0	1	0	0	0	0
Lochgilphead	186.000	688.000	3	-5.436	56.037	4	3	1	4	0	3	1	1	4	0	4	0	1	0	0	0	1	4	0	3	0	0	4	0	0
Lochranza	193.000	650.000	4	-5.294	55.699	5	5	0	5	0	5	0	0	4	0	4	0	0	4	1	1	3	2	2	2	0	2	3	0	0
Lochwinnoch	235.000	659.000	F	-4.632	55.796	2	2	0	2	0	2	0	0	1	0	1	0	0	1	1	1	1	1	0	1	0	0	2	0	0
Loudonhill	260.000	638.000	F	-4.223	55.615	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Machrie	190.000	633.000	F	-5.329	55.545	2	2	0	1	1	0	0	1	2	1	1	0	0	2	1	1	1	1	0	1	0	1	1	0	0
Maidens	221.000	607.000	4	-4.822	55.324	5	5	0	5	0	5	0	0	4	0	4	0	0	4	1	0	2	2	1	3	1	1	4	1	0
Maybole	230.000	610.000	3	-4.682	55.355	10	8	2	8	0	7	1	2	7	0	7	0	2	3	3	3	2	4	4	4	1	0	7	0	0
Milngavie	255.000	674.000	F	-4.322	55.937	3	2	1	2	0	2	0	1	0	0	0	0	1	1	0	0	1	1	1	0	0	0	2	0	0
Milton of Campsie	265.000	676.000	F	-4.163	55.958	1	1	0	1	0	1	0	0	1	0	1	0	0	0	1	0	0	1	1	0	1	0	1	0	0
Mollinsburn	272.000	672.000	F	-4.049	55.924	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	1	0
Moniaive	279.000	591.000	F	-3.901	55.198	2	2	0	2	0	2	0	0	2	0	2	0	0	1	0	0	0	0	1	0	0	0	2	0	0
Muasdale	169.000	640.000	3	-5.667	55.599	3	3	0	1	0	1	0	2	2	0	2	0	0	2	0	1	0	2	0	3	0	0	3	0	0
Muirkirk	269.000	627.000	F	-4.075	55.519	2	2	0	2	0	2	0	0	2	0	2	0	0	1	0	0	0	2	2	0	0	0	2	0	0
Murrayfield	322.000	673.000	2	-3.249	55.944	1	1	0	1	0	1	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0
Neilston	248.000	657.000	3	-4.424	55.782	4	4	0	4	1	3	0	0	3	0	3	0	1	1	2	0	0	4	0	4	0	0	4	0	0
New Abbey	296.000	566.000	F	-3.625	54.978	2	2	0	1	0	1	0	0	1	0	1	0	1	1	1	1	0	0	2	0	0	0	2	1	0
New Cumnock	262.000	613.000	3-4	-4.179	55.391	3	3	0	3	0	3	0	0	3	0	3	0	0	1	2	1	2	0	1	2	0	1	2	0	0
Newfield	292.000	572.000	F	-3.690	55.031	1	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Newmilns	253.000	637.000	3	-4.334	55.604	4	4	0	4	0	4	0	0	4	0	4	0	0	4	2	1	1	3	1	2	0	0	3	0	0
Newton	205.000	698.000	F	-5.138	56.135	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
Newton Mearns	254.000	656.000	4	-4.328	55.775	12	12	0	11	0	9	2	0	7	1	5	1	2	6	2	1	6	5	4	7	1	0	12	0	0
Newton Stewart	241.000	565.000	4	-4.483	54.954	7	7	0	7	1	6	0	0	5	0	5	0	2	4	3	2	4	2	4	2	1	0	6	0	0
Newtownabbey	148.000	537.000	F	-5.908	54.665	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Oban	177.000	716.000	F	-5.603	56.284	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Old Kilpatrick	247.000	673.000	F	-4.449	55.926	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Paisley	248.000	664.000	3-4	-4.428	55.845	28	27	1	23	2	18	3	3	14	3	9	2	7	13	8	3	11	14	8	15	4	3	22	2	0
Partick	255.000	667.000	3	-4.318	55.874	3	3	0	3	0	3	0	0	1	0	1	0	2	1	1	0	0	2	0	3	0	0	3	0	0
Patna	241.000	610.000	F	-4.509	55.358	2	2	0	1	0	1	0	1	1	0	0	1	1	1	0	0	0	1	1	0	0	1	0	0	0
Peebles	325.000	640.000	3	-3.192	55.648	4	4	0	3	0	3	0	1	1	0	1	0	0	2	2	0	3	1	0	3	0	0	4	0	0
Peninver	173.000	626.000	F	-5.592	55.475	1	1	0	1	0	1	0	0	1	1	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0
Pirnmill	187.000	644.000	F	-5.385	55.643	2	2	0	2	0	2	0	0	2	0	2	0	0	0	1	0	0	1	0	2	0	0	2	0	0
Pollockshaws	256.000	661.000	3	-4.299	55.821	5	5	0	3	0	3	0	2	2	0	1	1	3	0	1	0	2	3	2	1	1	0	5	0	0
Pollockshields	257.000	663.000	3	-4.284	55.839	17	16	1	15	2	13	0	2	8	0	8	0	9	4	3	0	5	11	3	11	0	1	15	0	0
Port Askaig/Caol Ila, Islay	143.000	669.000	F	-6.106	55.846	3	3	0	2	0	2	0	0	1	0	1	0	1	0	1	0	0	2	0	2	0	0	2	0	0
Port Ellen	137.000	646.000	F	-6.180	55.636	2	2	0	1	0	1	0	1	2	0	2	0	0	2	1	0	1	1	0	1	0	0	0	0	0
Port Glasgow	233.000	674.000	F	-4.673	55.930	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0
Portochoillan	178.000	658.000	F	-5.539	55.764	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Portpatrick	200.000	554.000	F	-5.115	54.841	2	2	0	2	0	2	0	0	2	0	2	0	0	1	0	0	0	2	1	1	0	0	2	0	0
Poundland	217.000	587.000	F	-4.872	55.143	1	1	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0	1	0	0
Prestwick - Monckton	235.000	626.000	4	-4.613	55.500	52	51	1	46	0	44	2	5	39	9	28	2	8	24	23	5	16	27	20	23	4	3	47	0	0
Rasharkin	112.000	569.000	F	-6.497	54.932	1	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Renfrew	250.000	667.000	F	-4.398	55.873	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Rhu	227.000	684.000	F	-4.776	56.018	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0
Riccarton/Earlston	242.000	635.000	F	-4.507	55.583	2	2	0	2	0	1	1	0	1	0	1	0	1	0	0	0	0	2	0	2	0	0	2	0	0
Roberton	295.000	629.000	F	-3.664	55.543	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Rothesay	209.000	664.000	F	-5.050	55.831	3	2	1	2	0	2	0	1	0	0	0	0	1	2	0	0	2	0	1	0	0	0	1	0	0
Rutherglen	261.000	660.000	3	-4.218	55.813	5	5	0	3	0	3	0	2	2	0	2	0	2	1	1	0	2	2	0	3	0	0	4	0	0
Saddell	176.000	634.000	F	-5.551	55.548	1	1	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saltcoats	225.000	642.000	4	-4.781	55.640	9	9	0	7	1	5	1	2	8	3	5	0	1	4	5	3	4	4	4	4	4	2	7	2	0
Sannox - Corrie	202.000	644.000	4	-5.147	55.649	6	6	0	5	0	5	0	1	5	1	4	0	0	3	2	1	4	2	4	2	0	1	5	0	0
Sanquhar	278.000	610.000	3	-3.925	55.369	3	3	0	2	0	2	0	1	1	0	1	0	2	1	1	0	1	2	0	3	0	0	3	0	0

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Placename	Grid East	Grid North	INT	LON	LAT	TOTAL RESPONSES	Positive Responses	Negative Responses	VIBRATION FELT TOTAL	FELT STRONGLY	MOD - UNSPEC	FELT WEAKLY	NOT FELT	NOISE HEARD TOTAL	LOUD NOISE	MOD - UNSPEC	SOFT NOISE	NOT HEARD	FELT - HEARD BY OTHERS	SELF ALARMED	OTHERS ALARMED	WINDOWS RATTLE	WINDOWS DO NOT RATTLE	OBJECTS RATTLE	OBJECTS DO NOT RATTLE	HANGING - SWING	OBJECTS UPSET	OBJECTS ARE NOT UPSET	DAMAGE - B1	DAMAGE - B2
Shieldhill	299.000	677.000	F	-3.619	55.975	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0
Skelmorlie	220.000	667.000	F	-4.877	55.863	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0
Sliddery	193.000	623.000	F	-5.274	55.457	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	0
Slockavullin	182.000	698.000	1	-5.508	56.125	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Smerby Mill	175.000	623.000	F	-5.558	55.449	1	1	0	1	1	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
St Andrews	350.000	716.000	1	-2.809	56.334	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Stevenston	227.000	642.000	4	-4.749	55.641	11	11	0	9	2	6	1	2	6	2	4	0	1	7	2	1	6	5	7	3	0	0	11	0	0
Stewarton	241.000	645.000	3-4	-4.529	55.672	9	9	0	8	0	7	1	1	6	2	3	1	0	5	2	2	3	6	4	3	1	1	8	0	0
Stranraer	206.000	560.000	F	-5.026	54.897	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0
Strathaven	270.000	644.000	F	-4.067	55.672	3	3	0	2	0	1	1	1	2	0	2	0	1	0	1	0	3	0	2	1	0	1	2	0	0
Symington	238.000	631.000	3-4	-4.568	55.546	4	4	0	4	0	4	0	0	4	1	3	0	0	3	1	1	2	2	2	0	0	0	4	0	0
Tarbert	186.000	668.000	3	-5.420	55.858	5	5	0	5	0	5	0	0	5	0	5	0	0	3	1	1	3	2	1	4	1	0	0	0	0
Tarbolton	243.000	627.000	F	-4.487	55.511	2	2	0	2	0	2	0	0	1	0	1	0	0	1	2	1	0	2	0	2	0	0	2	0	0
Tayinloan	170.000	646.000	F	-5.656	55.653	1	1	0	1	0	0	1	0	1	0	1	0	0	1	0	1	1	0	1	0	0	0	1	0	0
Thornhill	288.000	595.000	F	-3.761	55.236	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1	0	1	0	0	1	0	0	1	0	0
Thornliebank	255.000	659.000	3	-4.314	55.803	5	4	1	3	0	3	0	1	0	0	3	0	1	1	1	1	1	2	1	1	0	0	4	0	0
Tollcross	264.000	664.000	F	-4.173	55.850	2	2	0	2	0	1	1	0	0	0	0	0	2	0	0	0	0	2	0	2	0	0	2	0	0
Torrance	262.000	674.000	F	-4.210	55.939	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Trabbock	244.000	622.000	F	-4.468	55.467	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0
Troon	232.000	631.000	4	-4.663	55.544	31	27	4	23	1	20	2	7	26	4	22	0	6	7	8	1	12	11	9	14	2	2	24	1	0
Turnberry	220.000	605.000	F	-4.836	55.306	2	2	0	2	1	1	0	0	2	0	2	0	0	2	2	2	2	0	1	0	0	0	2	1	0
Uddingston	270.000	660.000	3	-4.075	55.816	3	3	0	3	0	3	0	0	0	0	0	0	2	0	0	0	0	2	1	2	0	0	3	0	0
Uplawmoor	243.000	655.000	3	-4.503	55.763	7	7	0	6	0	6	0	1	3	0	3	0	3	2	1	1	1	5	3	4	0	1	6	0	0
Waterbeck, Lockerbie	326.000	578.000	1	-3.160	55.091	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0
Waterside	248.000	643.000	F	-4.416	55.657	1	1	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0
Wemyss Bay	219.000	670.000	F	-4.895	55.889	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0
West Kilbride	220.000	648.000	3-4	-4.864	55.692	13	12	1	11	0	11	0	2	6	1	3	2	7	1	3	0	8	4	4	7	0	1	11	0	0
Whitehouse	182.000	661.000	3	-5.478	55.793	3	3	0	2	0	2	0	1	3	0	3	0	0	2	0	0	2	1	0	3	0	0	3	0	0
Whiting Bay	204.000	625.000	4-5	-5.102	55.479	21	21	0	17	3	12	2	3	19	11	8	0	2	13	5	5	9	9	4	12	3	1	19	2	0
Wigtown	242.000	554.000	F	-4.462	54.856	1	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Wishaw	280.000	655.000	1	-3.913	55.773	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
						824	772	52	666	43	575	48	143	572	120	437	18	172	299	244	104	280	391	244	376	70	65	657	22	0

TABLE 8 - SYNOPSIS OF RESPONSES FOR THE ARRAN EARTHQUAKE OF 4 MARCH 1999

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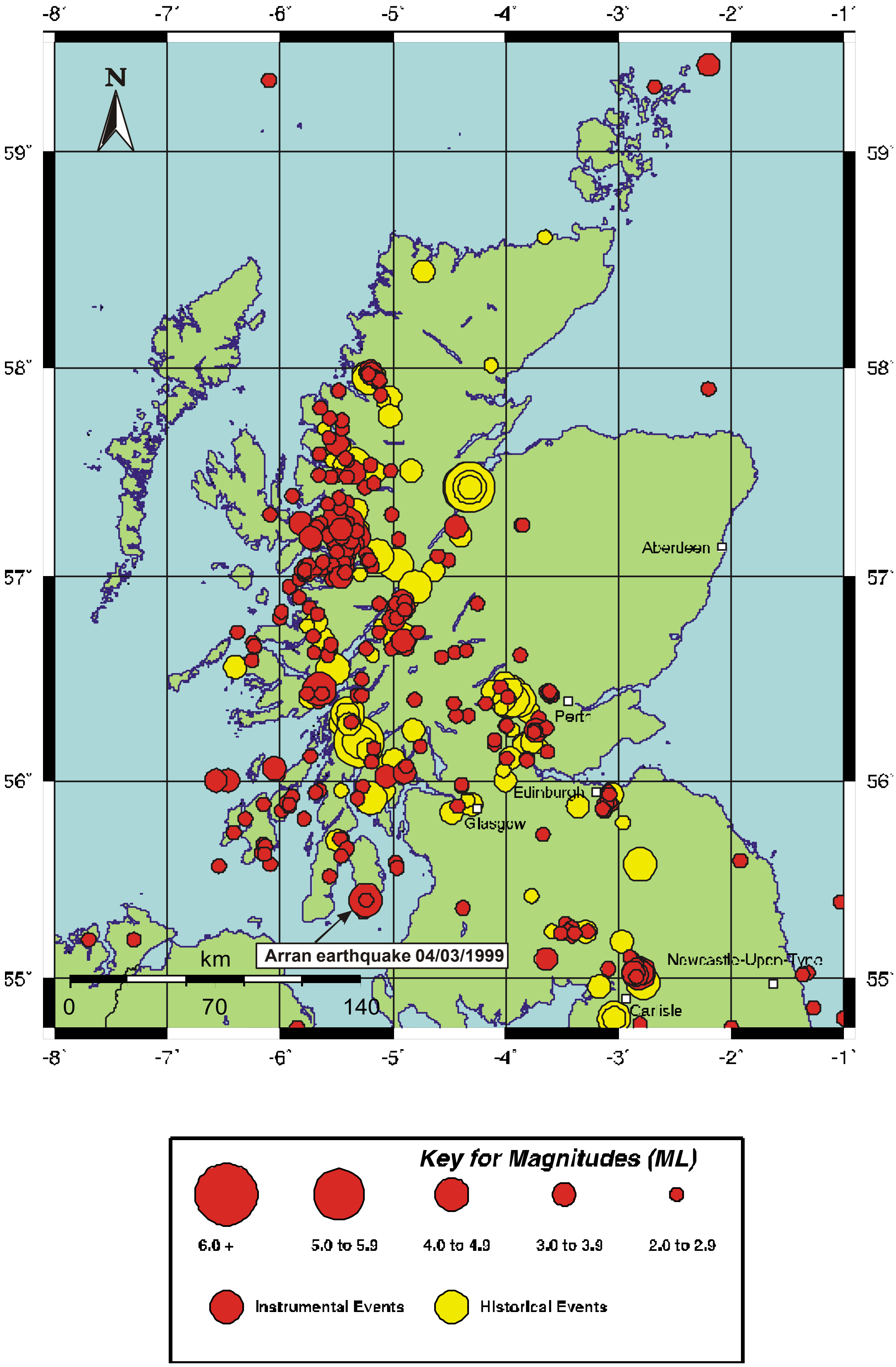


Figure 1. Instrumental (ML > 2.0) and historical seismicity of Scotland.

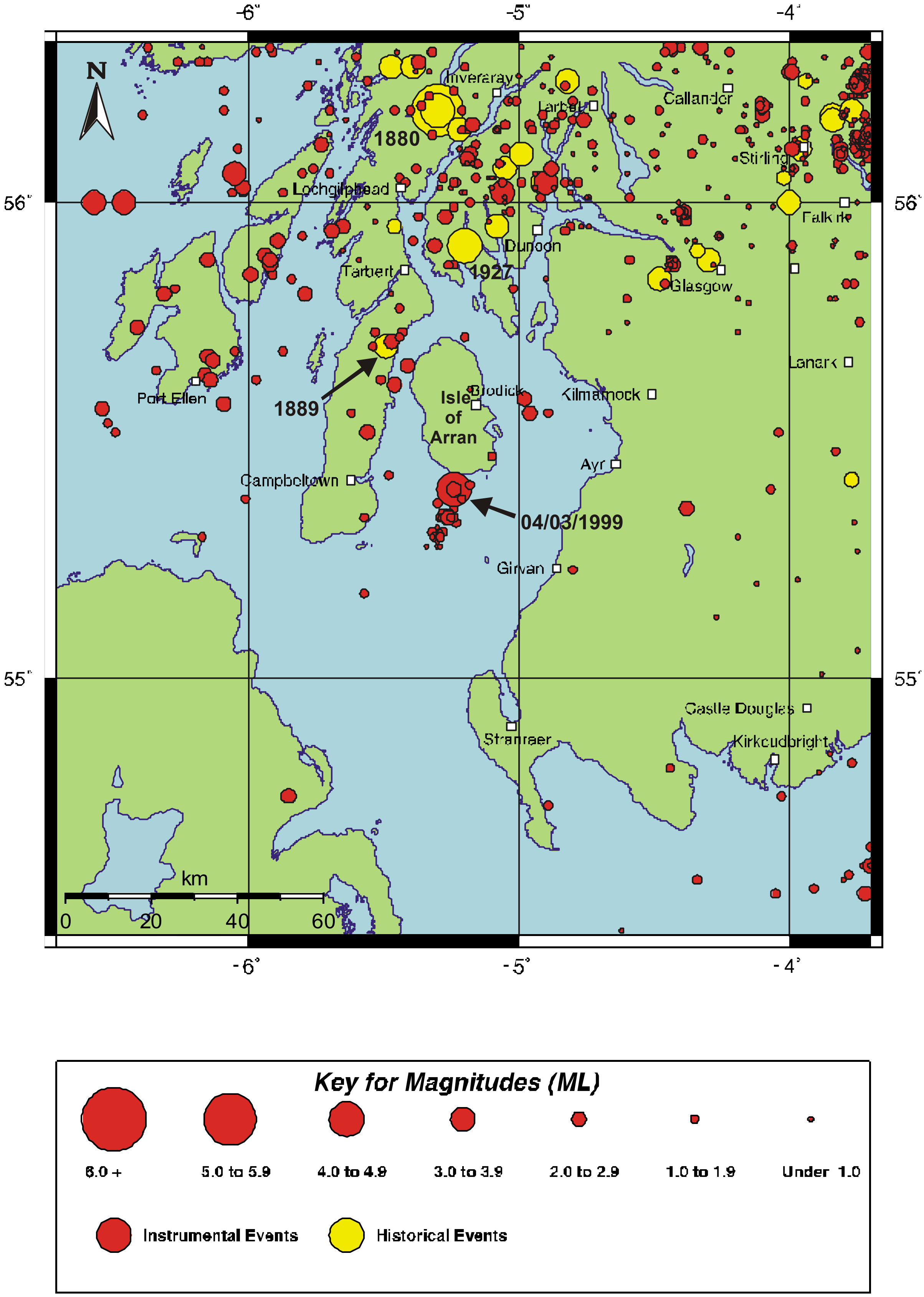


Figure 2. Instrumental and historical seismicity of the region around Arran

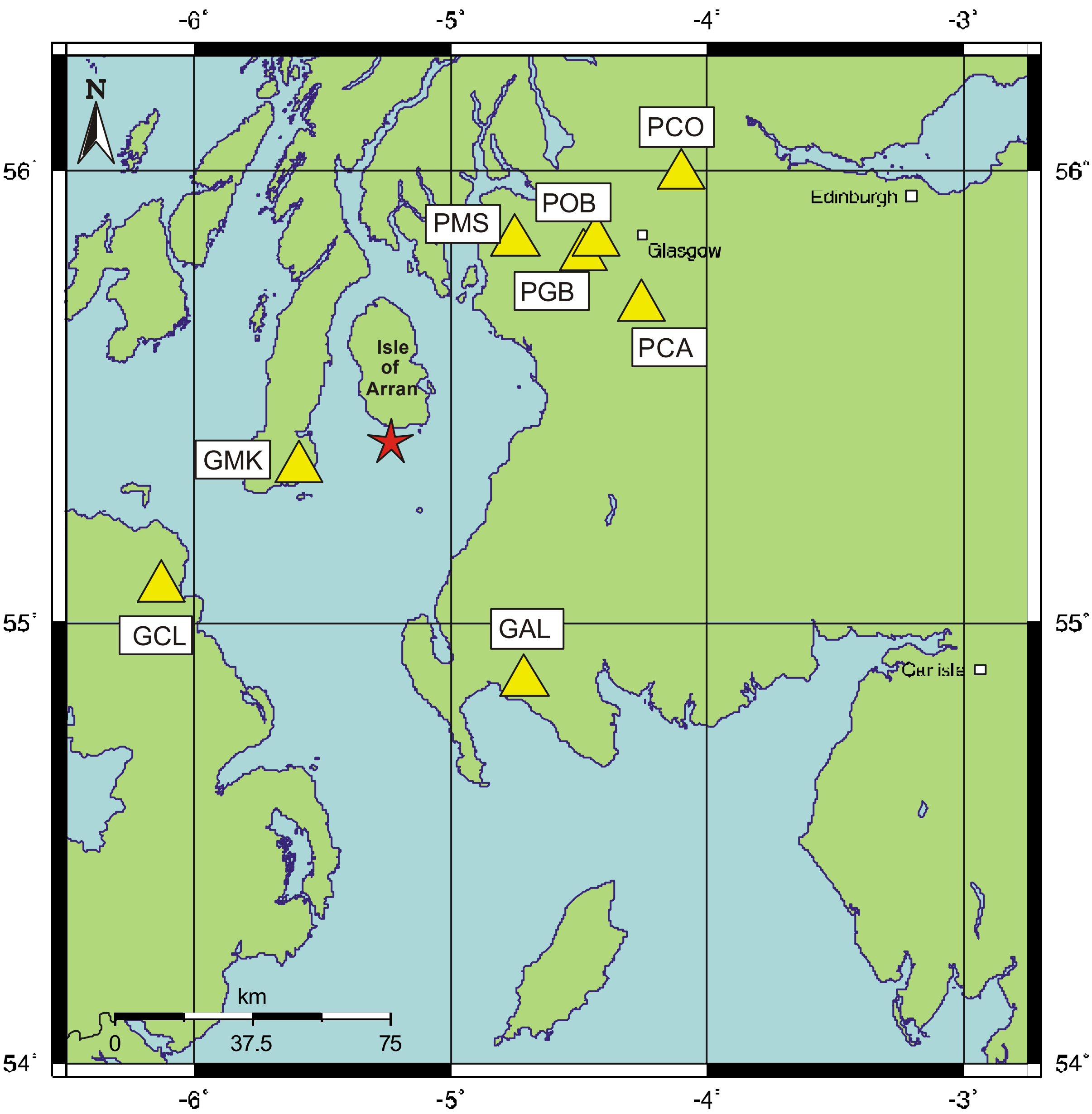


Figure 3. Stations used in locating the 4 March 1999, Arran earthquake. Red star represents epicentre.

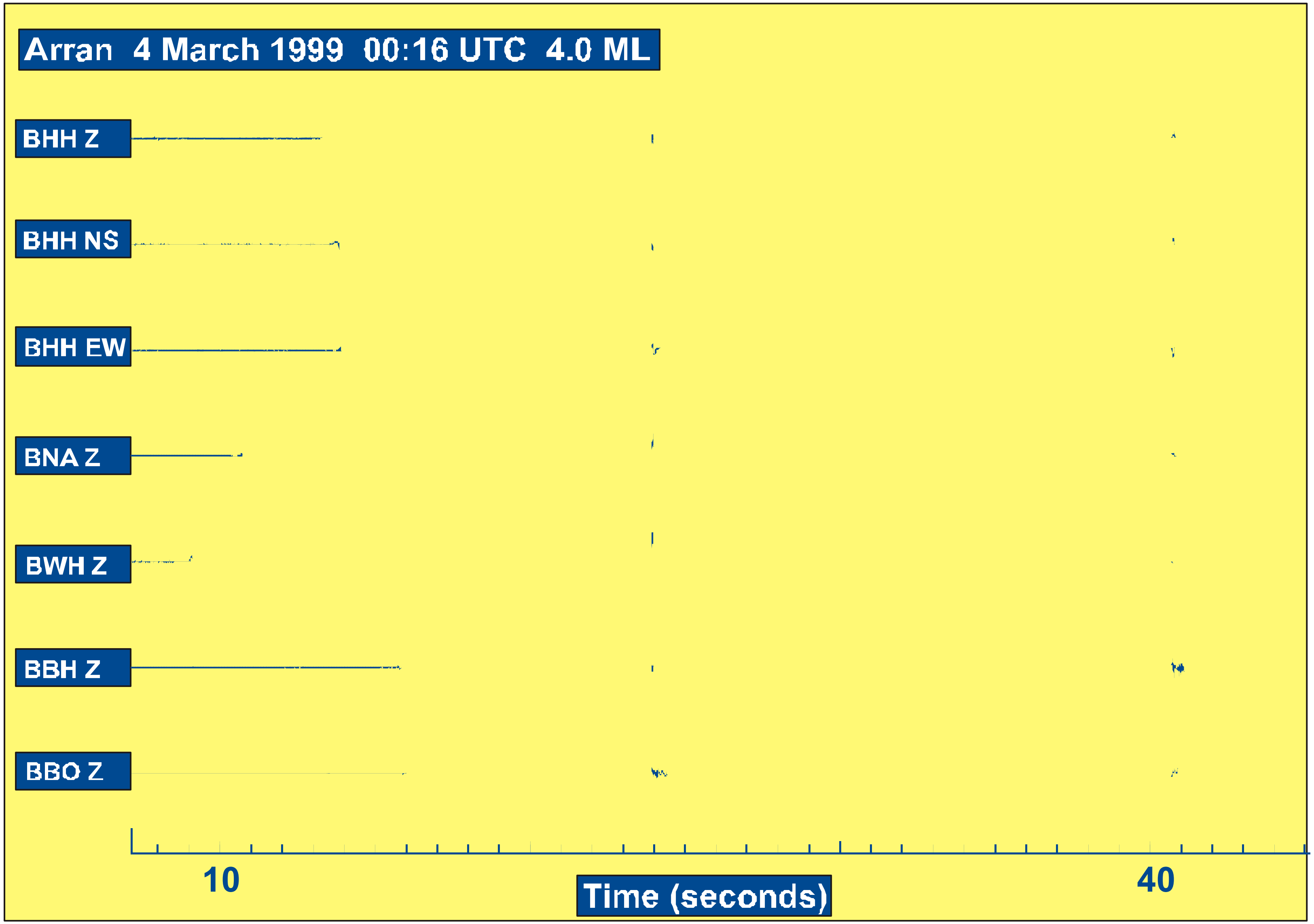


Figure 4. Seismograms recorded on the Borders network stations of the 4 March 1999 4.0 ML Arran earthquake.

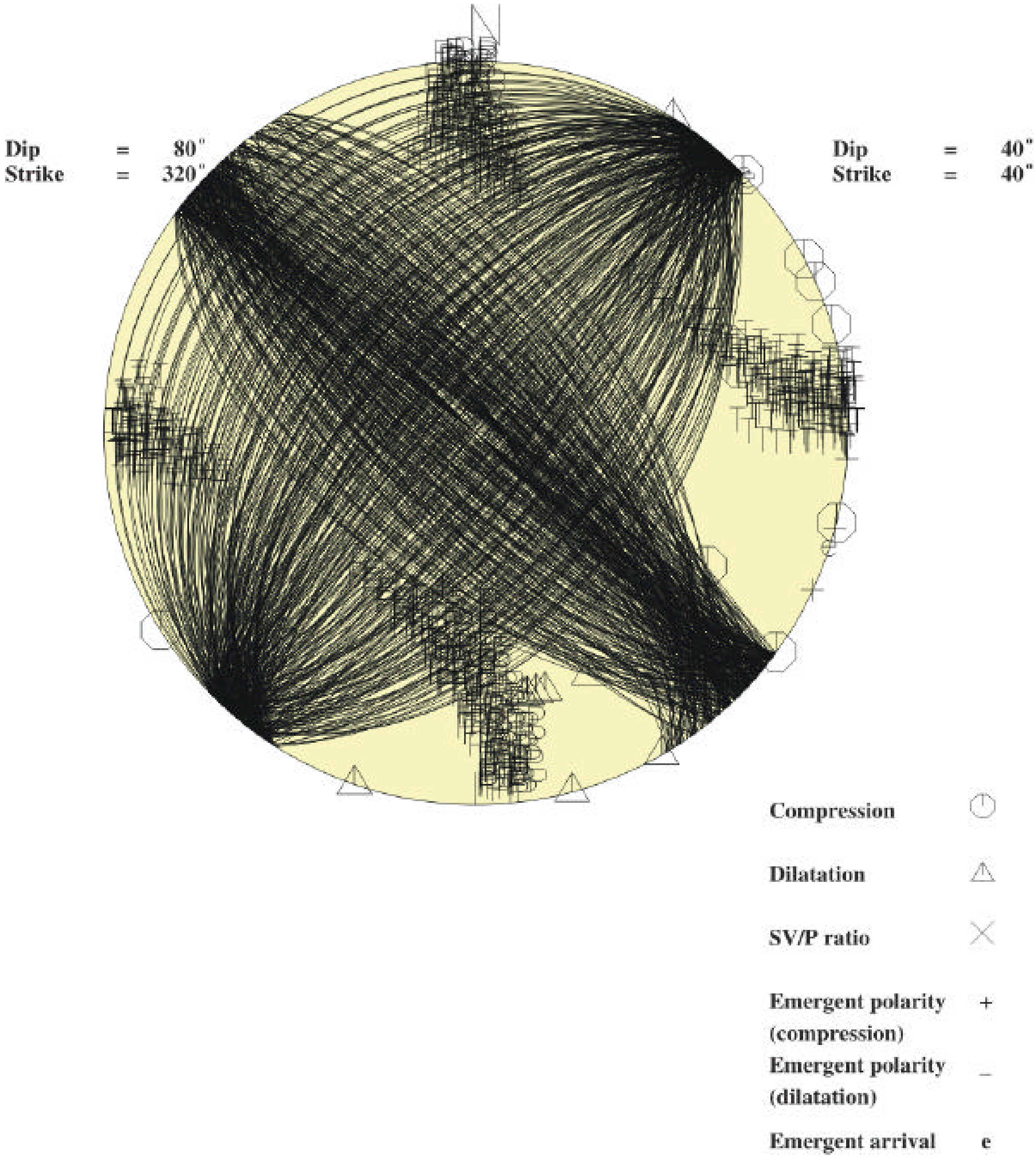


Figure 5. Equal area projection of the lower hemisphere for the Arran earthquake of 4 March 1999, 4.0 ML. The axes of maximum and minimum compressive stress are denoted by P and T respectively.

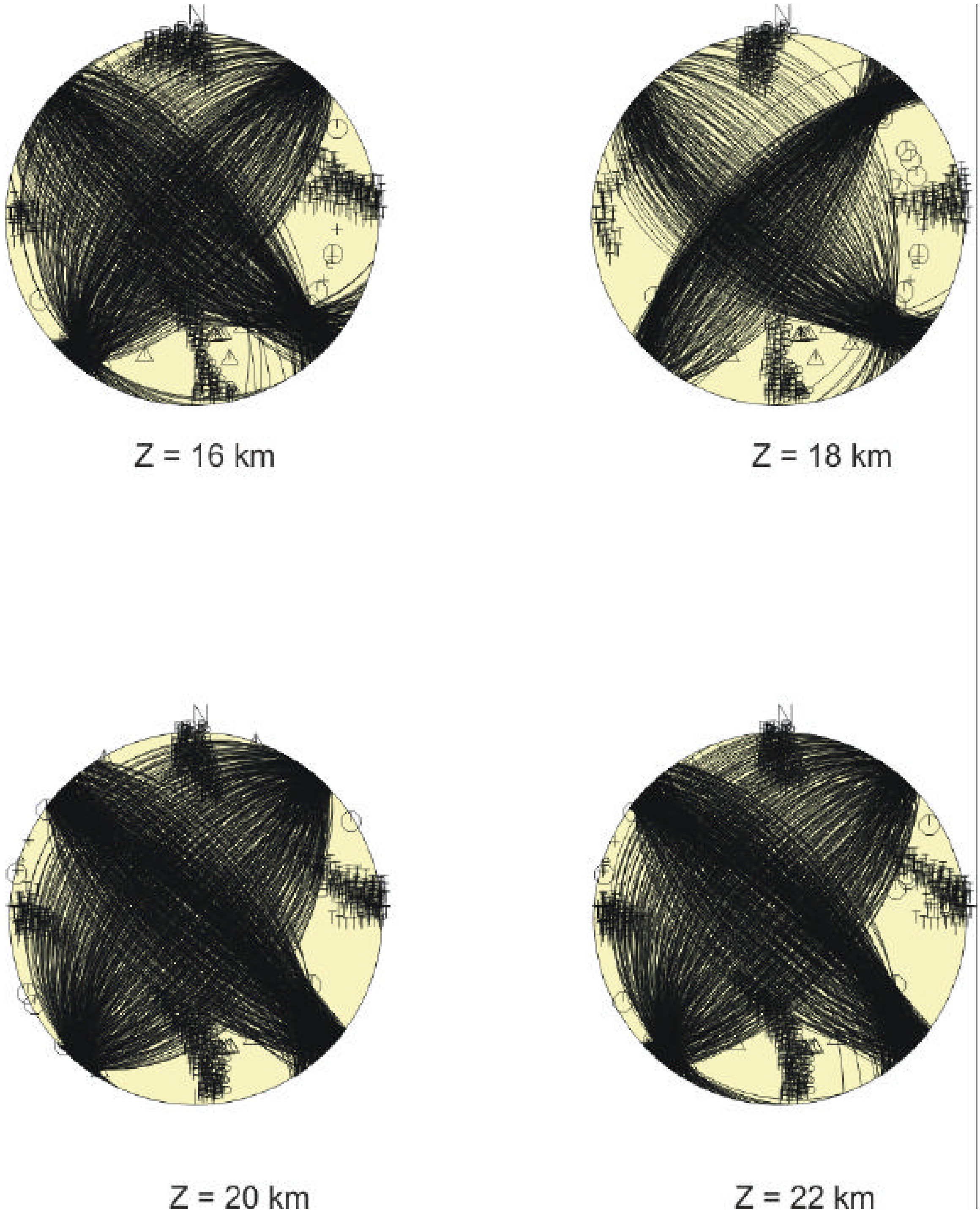


Figure 6. Focal mechanisms (lower hemisphere projection) for the Arran earthquake of 4 March 1999, 4.0 ML, for various fixed depths.

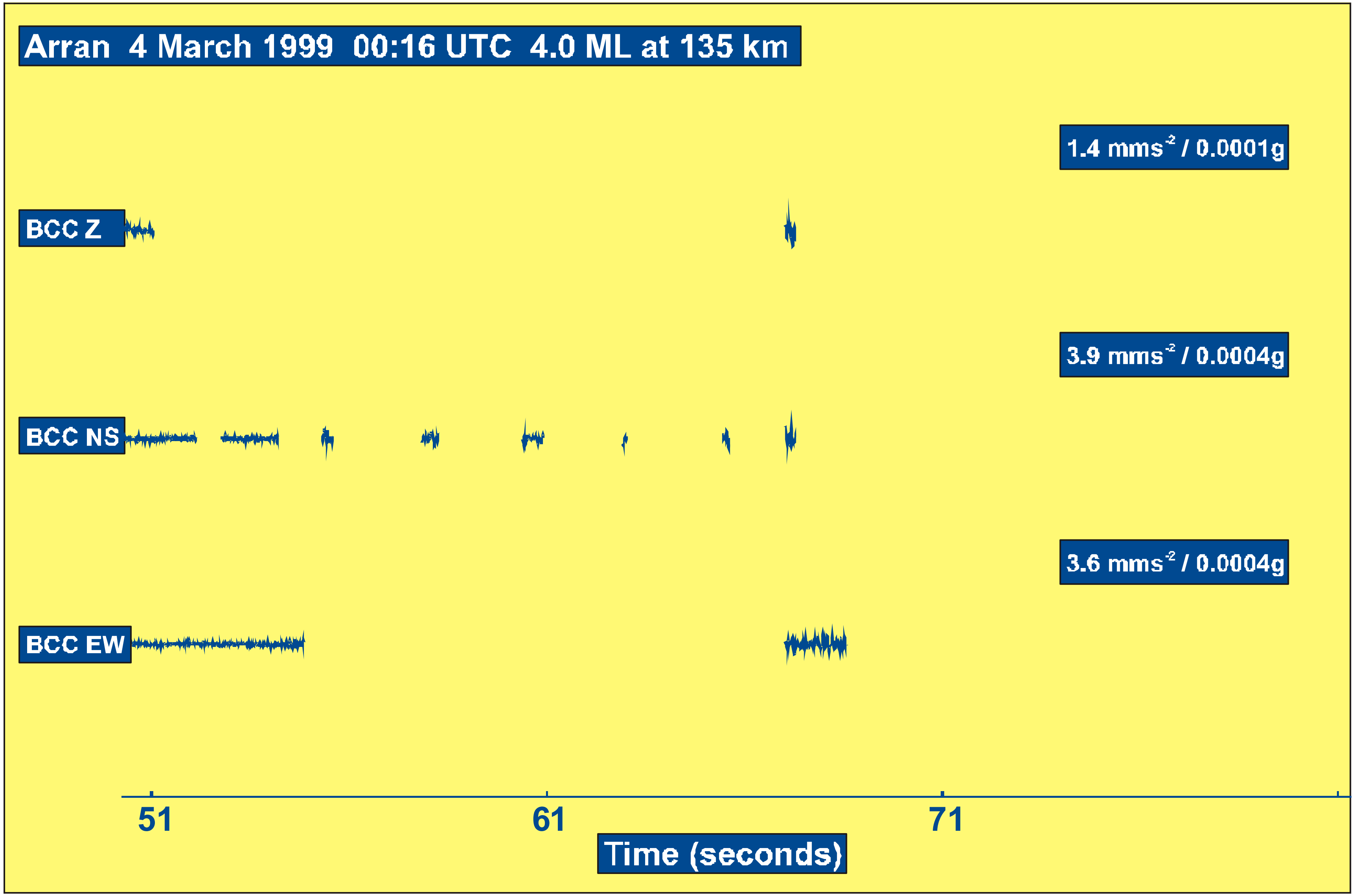


Figure 7. Ground accelerations measured on the strong motion instrument at Chapel Cross (BCC) of the Arran earthquake of 4 March 1999, 4.0 ML, at 135 km

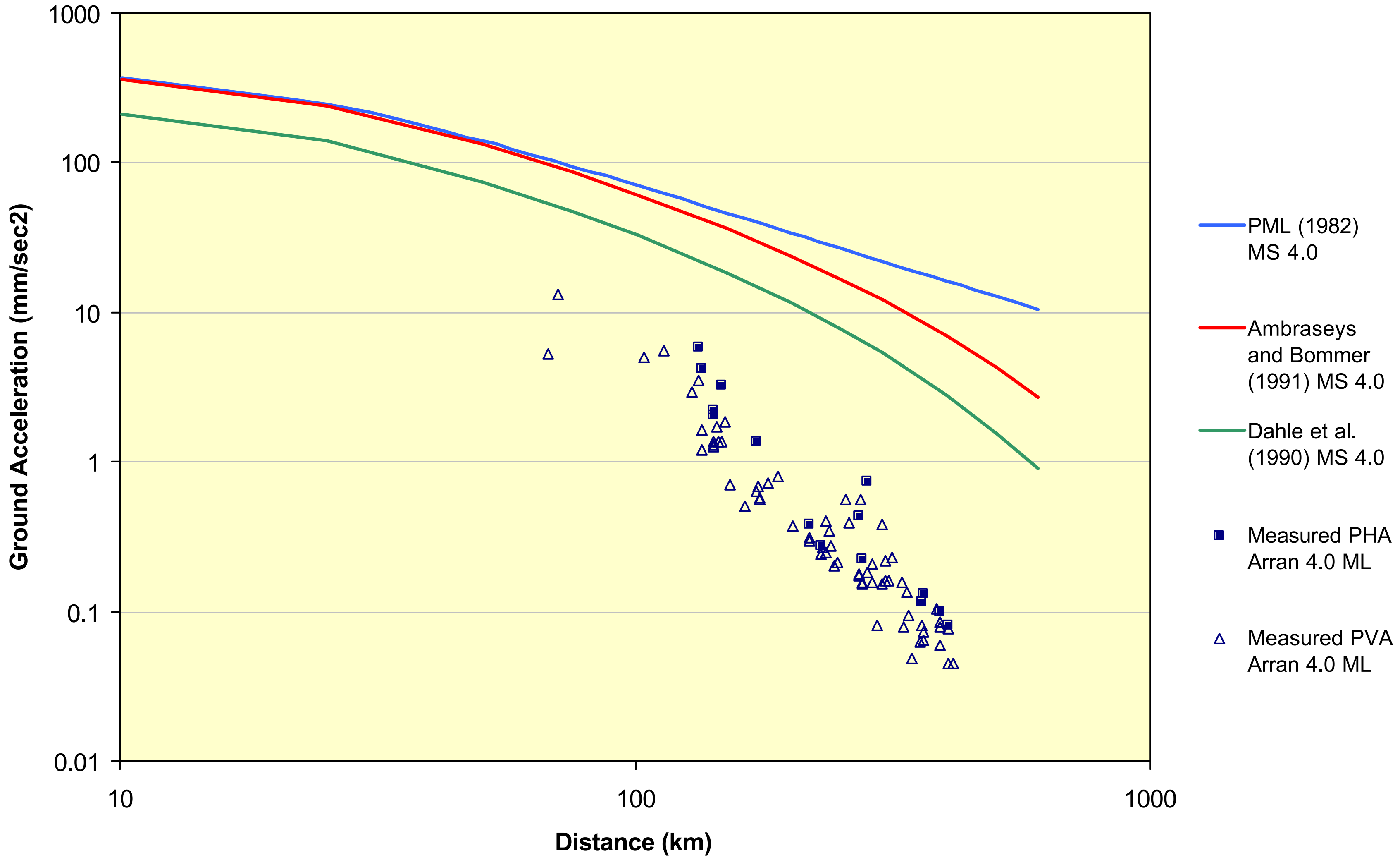


Figure 8. Measured peak horizontal (filled squares) and vertical (triangles) ground acclerations and expected horizontal accelerations for three empirical attenuation relations, with epicentral distance (km).

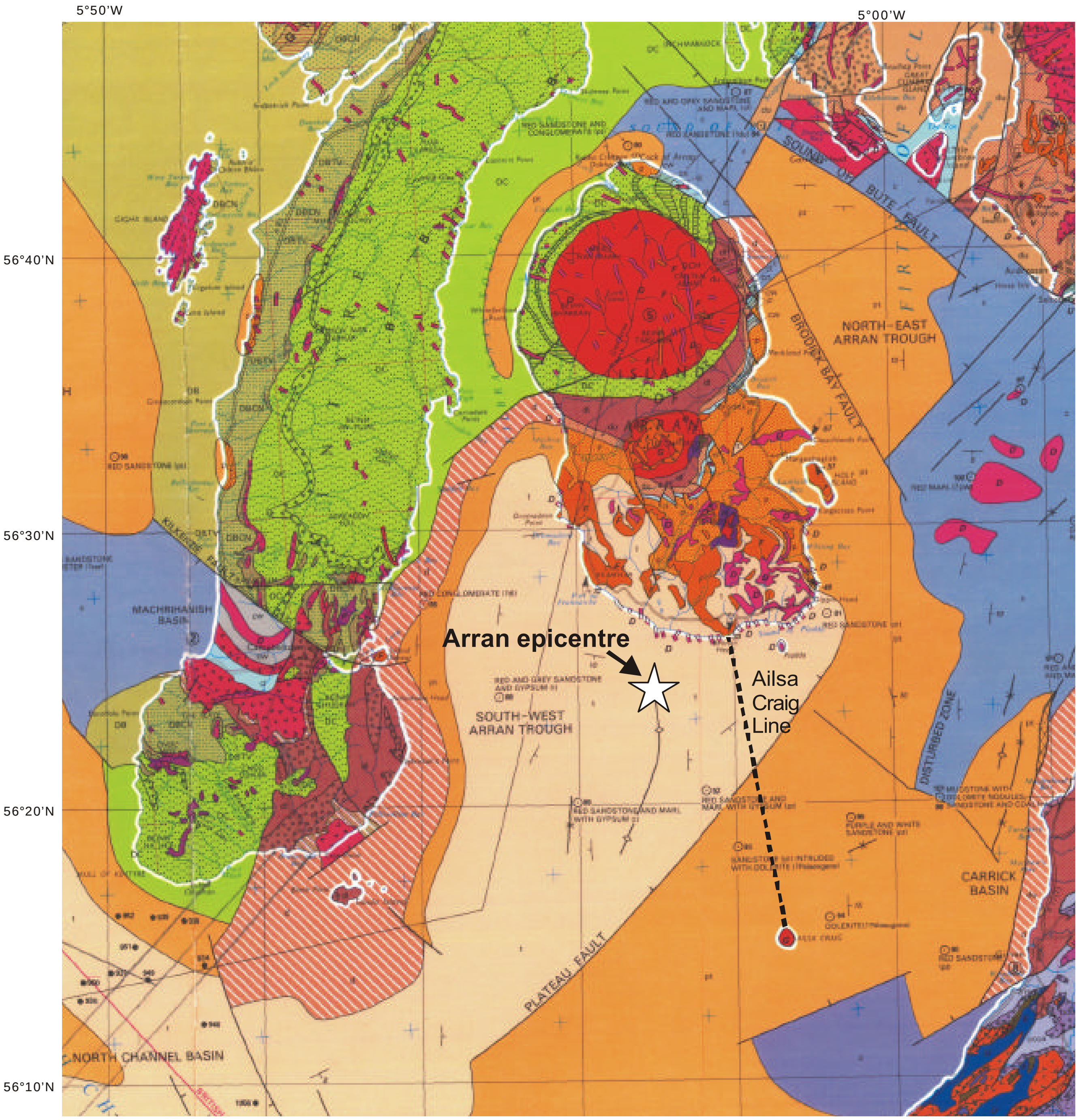


Figure 9. Solid geology of the Arran, Firth of Clyde and Kintyre region (McAdam et al, 1985). The approximate location of the Ailsa Craig Line is also plotted (dashed line).

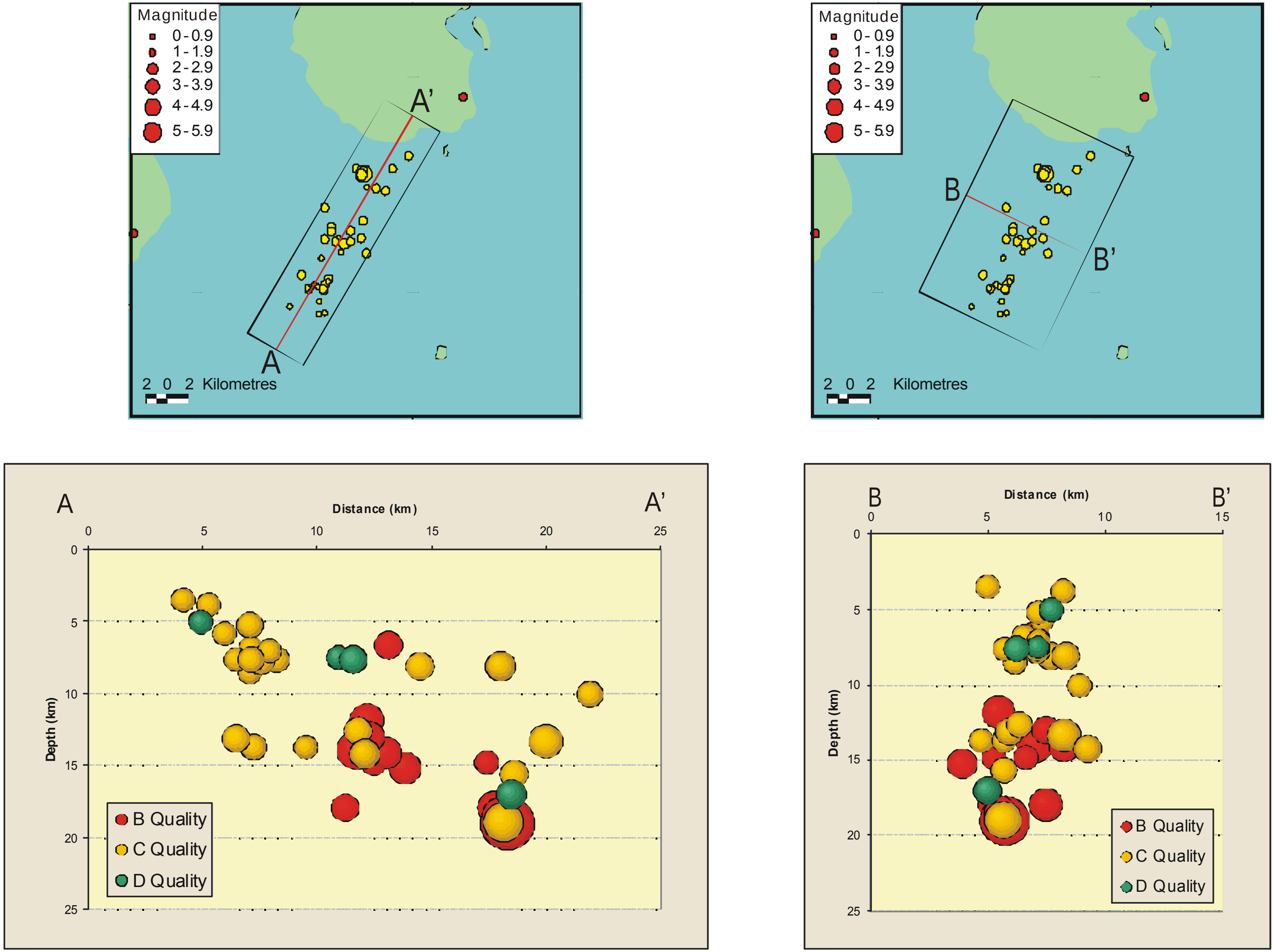


Figure 10. Cross sections NNE-SSW (A-A') and WNW-ESE (B-B') through the three clusters of earthquakes around the 1999 Arran event. Size of circle is proportional to magnitude and colour represents the location quality.

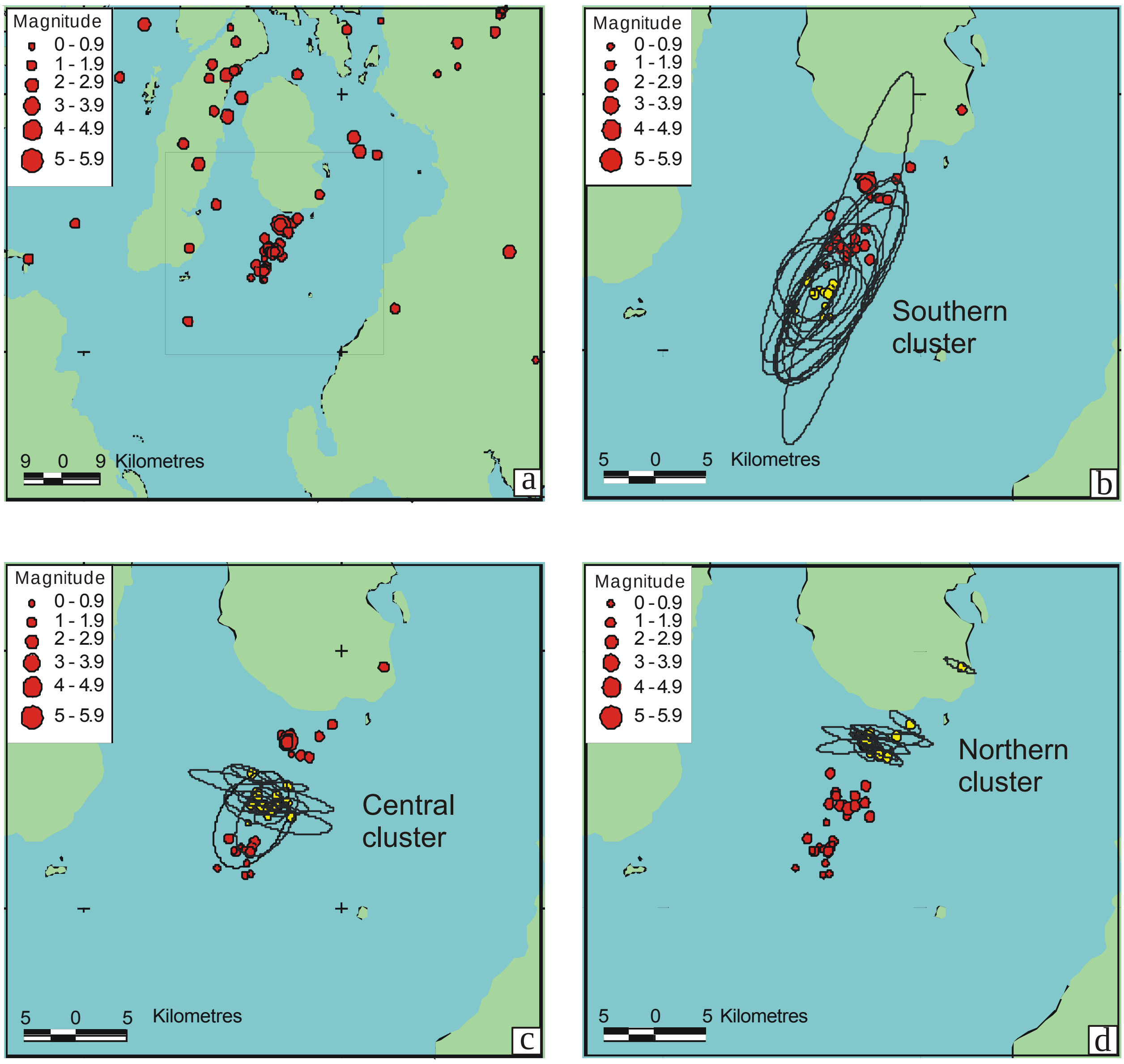
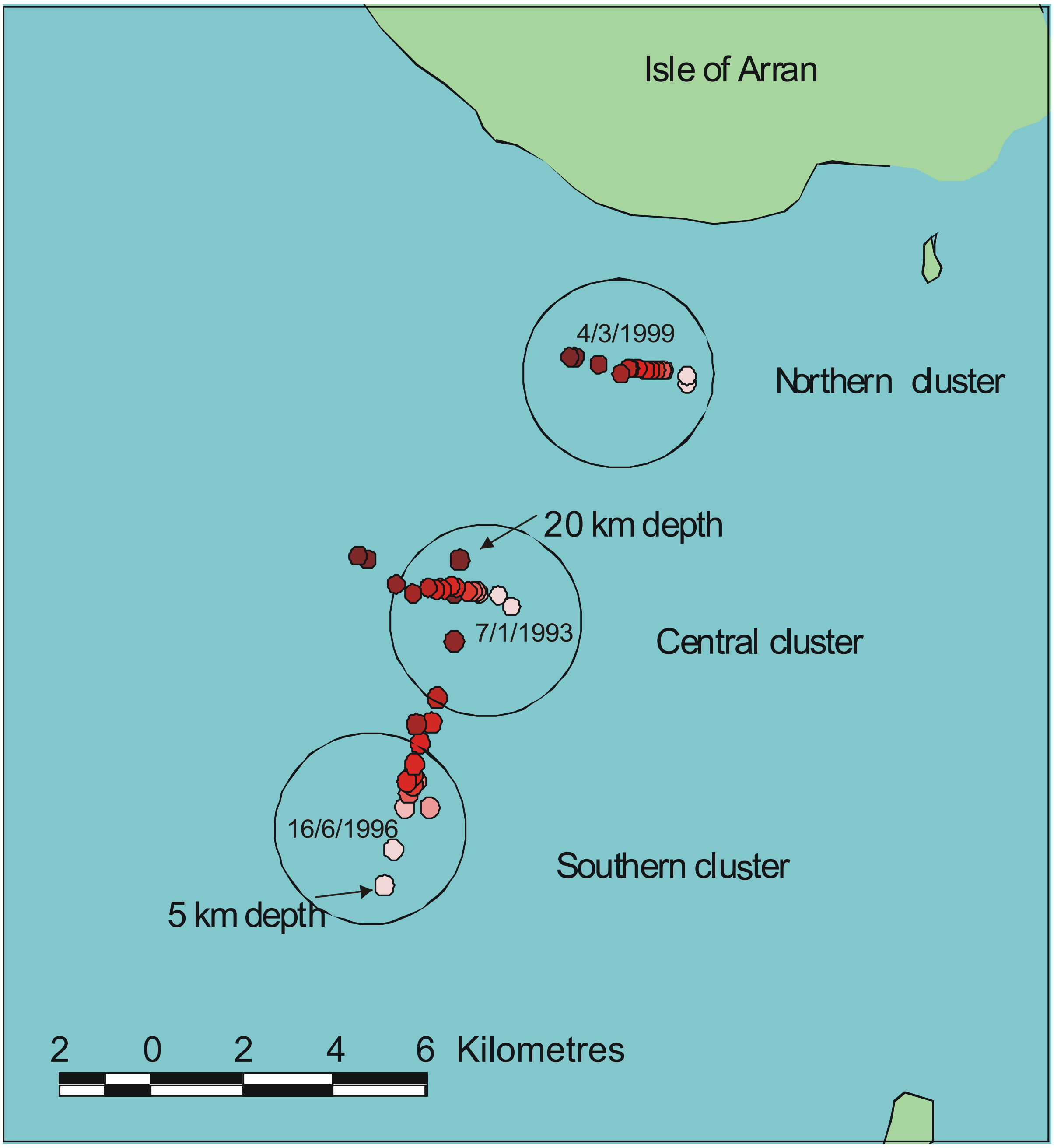


Figure 11. a) Regional map of instrumental seismicity and inset of study area
b) Error ellipses for southern cluster
c) Error ellipses for central cluster
d) Error ellipses for northern cluster

Events showing error ellipses are highlighted in yellow in each case.
Only events in the Arran clusters are shown in b), c) and d).



Locations are colour coded with pale pink for 5 km depth, darkening as depth increases to brown for 20 km depth

Figure 12. Locations for selected events from each of the three clusters as a function of fixed depth

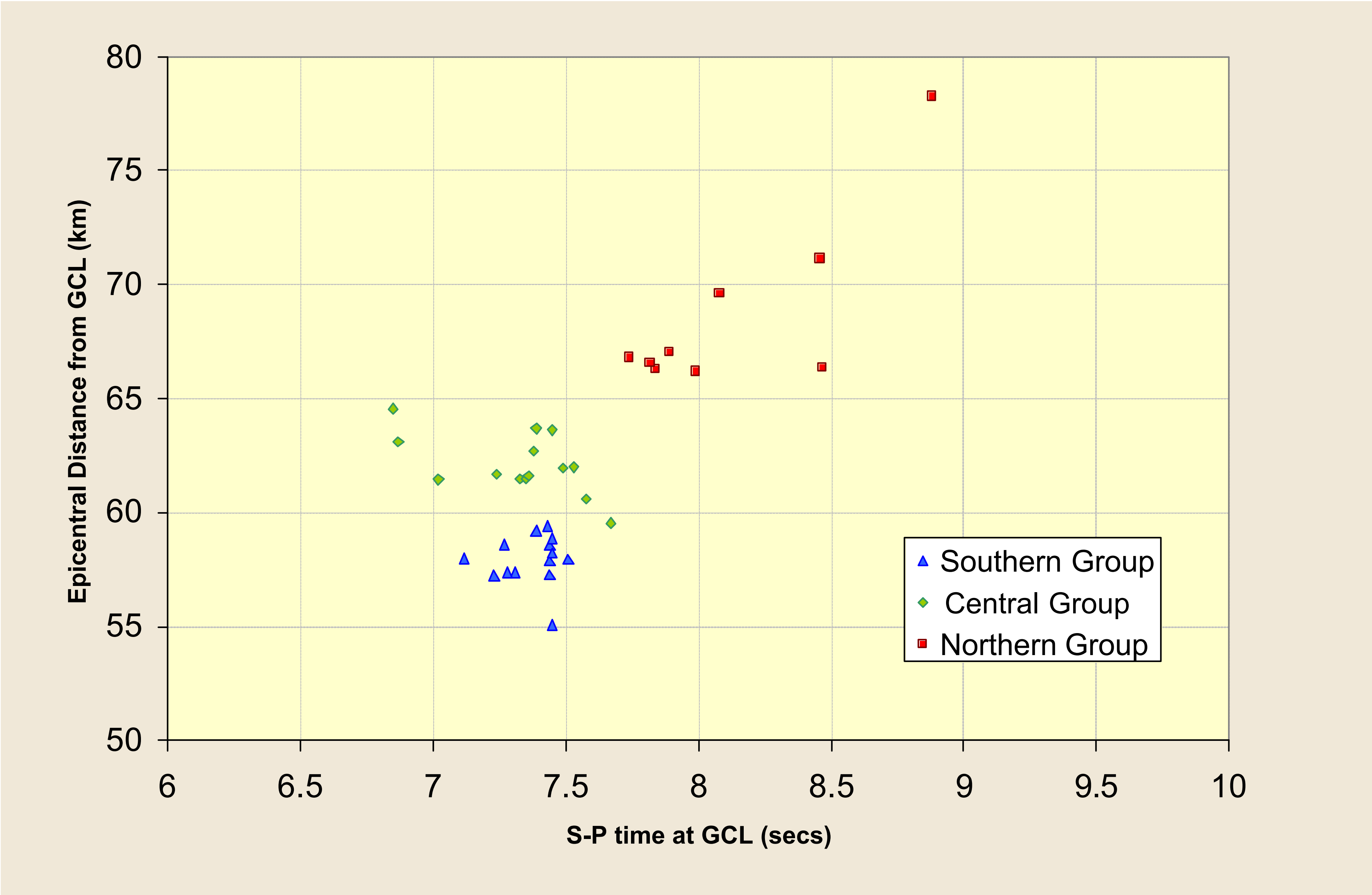


Figure 13. S-P time measured at station GCL in seconds plotted as a function of epicentral distance for all the Arran events

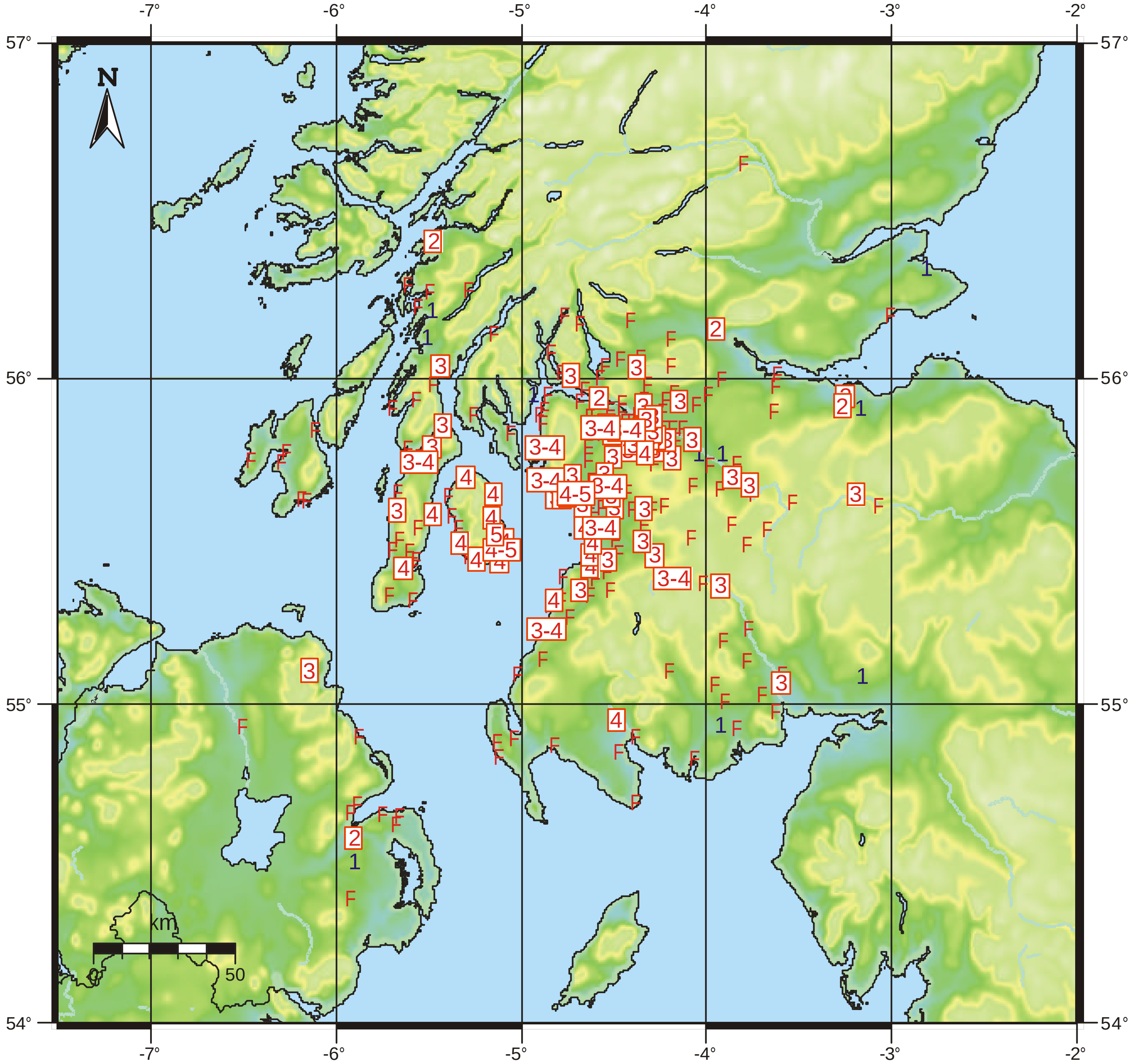


Figure 14. Macroseismic data collected for the 4 March 1999 magnitude 4.0 ML Arran earthquake.

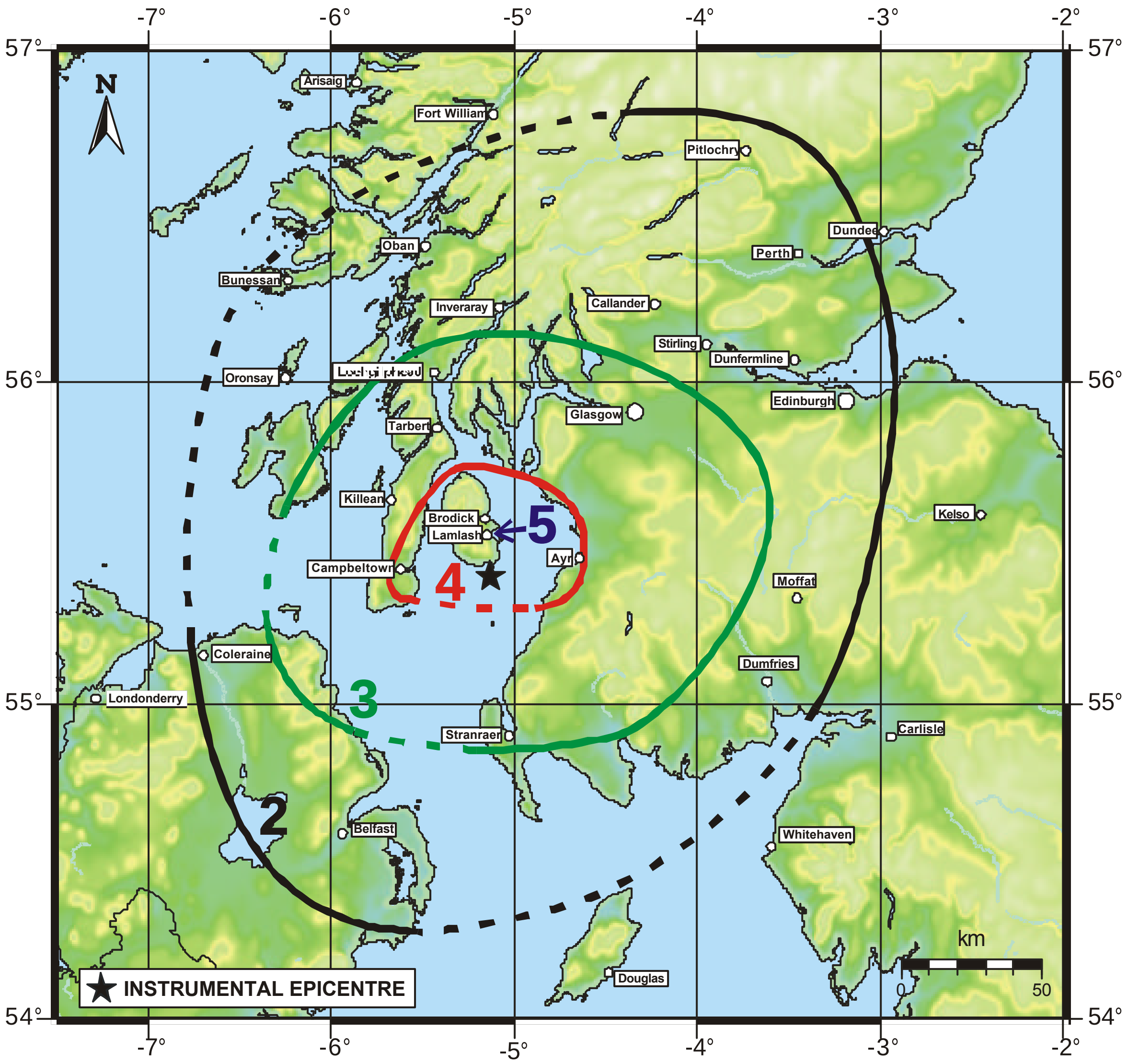


Figure 15. **Isoseismal map of the 4th March Arran earthquake. Intensity values are in EMS (Grünthal, 1998).**