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RECORD 1982/30

SEISMIC MONITORING OF THE PROPOSED BURDEKIN FALLS DAM

A Preliminary Report to June 1982

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SUMMARY

The monitoring of the proposed Burdekin Falls dam becomes important in the light of previous experiences, both overseas and in Australia, where the impounding of a large volume of water has sometimes induced earthquakes, even in areas that were previously regarded to be aseismic.

The Burdekin Falls dam area has, at least at one stage, been active as is evidenced by the faulting and folding in the region. Several of these faults are of a significant length and could perhaps be related to other faults outside the region being studied. A number of earthquakes that have been felt by people in the area in recent history indicates that the area is still active, albeit at a low level.

A three station microearthquakes network has been operating in the vicinity of the proposed reservoir for the past 18 months. In this period 34 events ranging in magnitude from -1.0 to 2.7 have been located within a 100 kilometre radius of the dam.

The installation of a seven station network is strongly recommended in order that the activity in the area can be studied in more detail.

INTRODUCTION

The association between seismicity and the filling of large reservoirs was first recognised in the mid-1930's at Lake Mead (Hoover Dam) (Carder, 1945). Since then, due to the increase in research into the phenomenon as well as the increase in size of reservoirs, there have been numerous documented examples of reservoir induced seismicity. For a general summary the reader is referred to Simpson (1976). The potential for damage due to induced earthquakes is generally higher than that for tectonic earthquakes because the induced events are of relatively shallow focal depth (less than 7 km). When this fact is combined with the vulnerability of a dam wall during an earthquake as well as the potential for damage should the dam fail, then the study of this phenomenon becomes important.

The National Academy of Sciences report (1972) defines a large reservoir as "one with a volume of one million acre-feet (1 233.5 x $10^6 m^3$) or more, usually impounded behind a dam 300 ft (91.4 m) or greater in height". It is now generally agreed that any large reservoir should be monitored for induced seismicity. It should be noted here that a majority of "large" reservoirs have been shown to be aseismic and a minority of smaller ones seismic. Other factors which may influence whether a reservoir is to be monitored include:-

- Existing "natural" seismicity
- State of stress in the crust
- Existing fractures and faults
- Possible damage should an induced earthquake occur.

Using the above criteria the proposed Burdekin Falls dam (see Figure 1 for a location map), with a volume of $1\,750 \times 10^6 m^3$ at FSL, can be classified as a large reservoir and as such should be monitored for the possibility of induced seismicity.

In order to obtain an estimate of the natural or "background" seismicity of an area monitoring should commence well before the reservoir is filled. In most cases a five year period of pre-impounding monitoring should be sufficient but this may be impossible due to funding or logistics.

The basic aim of any monitoring programme is to determine the frequency, location, depth and magnitude of any local earthquakes that occur both before and after the reservoir is filled. If such activity does occur then focal mechanisms should be sought and the nature of faulting ascertained. Once the reservoir has been filled for a suitable period a comparison between pre- and post-impounding activity should indicate if the reservoir was responsible for inducing any earthquakes.

It is extremely unlikely that pre-impoundment monitoring will be able to do more than to identify the "tectonic state" of the area and to indicate whether this state is favourable or unfavourable in regard to reservoir induced seismicity. Any monitoring programme will provide a limited amount of data for seismic risk analysis but care must be taken in extrapolating these data from what is geologically a very short period.

To locate an earthquake a minimum of three seismographs is necessary (if locations are not required then one seismograph is sufficient). It is prudent to install more seismographs to guard against instrument failure. The number of seismographs actually installed depends on the location accuracy that is desired as well as the size of the area being monitored (see section 'Number of Instruments' in chapter on Proposals).

TECTONICS AND STRUCTURAL GEOLOGY

Figure 2 indicates the major structural units of the area together with the coverages and titles of the relevant 1:250 000 geological maps. The structural geology information was taken from the explanatory notes for the various 1:250 000 geological

maps: Ayr (Gregory, 1969), Bowen (~~Parke~~ Paine & Cameron, 1972), Mount Coolon (Malone, 1969), Buchanan (Olgers, 1969a) and Charters Towers (Clarke & Paine, 1978). Structural geology for the Townsville sheet area was taken from Levingstone, 1981.

The inundated area of the proposed reservoir is in the northern end of the Drummond Basin. The Drummond Basin is a Late Devonian/Early Carboniferous basin which laps onto the basement rocks of the Lolworth-Ravenswood Block and at least locally onto the Anakie Inlier. The basin in turn is overlain by the Galilee and Eromanga Basins to the west and by the Bowen Basin and Late Carboniferous volcanics to the east (Olgers, 1969a).

The major faults and shear zones of the area are shown in Figure 3, together with the coverages of the relevant 1:250 000 sheet areas (as in Fig. 2). The offshore faults in the Ayr sheet area are taken from Rasidi & Smart (1979). To the northwest, in the Townsville sheet area, there are two sets of faults. One set trends northwest inland, turning westerly towards the coast, while the second set trends northeast inland, turning to an east-north-east direction toward the coast (Wyatt, 1968). In the Charters Towers and Buchanan sheet areas there are no clear predominant directions of faulting although there are northwest, northerly and northeast trends. The Belyando Feature in the western side of the Buchanan sheet area has been detected by seismic exploration. It is exhibited at the surface in some places as a monocline and is thought to be a large reverse fault, east block up, that was active at the end of the Early Carboniferous (Olgers, 1969a).

In the Mount Coolon and the eastern half of the Bowen sheet areas the major faults trend in a northwest or a north-northwest direction. This trend is continued with the offshore faults to the north and with faults in the two sheet areas to the east (Proserpine and Mackay). The Millaroo Fault Zone appears to separate this region of northwest and north-northwest trending faults from the area with less regular trends to the west (Paine & Cameron, 1972). Levingston (1981) has extended the Millaroo Fault zone, mainly on the basis of physiographic expression, northwest through the Ayr and Townsville sheet areas. At this point the extension of the Millaroo Fault would coincide with the southern extension of the large Palmerville Fault to the north (de Keyser, 1963).

Most faults in the Almoola Hinge Zone (Paine & Cameron, 1972) as well as the major fault in the Mount Coolon sheet area (Malone, 1969) are reverse faults with the east block uplifted. The Collinsville Fault in the Almoola Hinge Zone is a reverse fault with a throw of over 200 metres (Webb & Crapp, 1960). The Saint Anns and associated faults are also considered to be reverse faults with the eastern block uplifted

(Olgers 1969b), as is the case with the Belyando Feature mentioned earlier. In contrast, Gregory (1969) states that the Millaroo Fault is probably a normal fault with the east block down.

Wyatt (1969) has noted that movements of faults in the Townsville sheet area are dominantly strike-slip in the coastal range area, but mainly dip-slip inland. Displacements of 12 miles horizontally and 15-20 000 feet vertically have been inferred.

In some areas (Alex Hill, Mosgardies and Inkerman Shear Zones) deformation is expressed as shear foliation.

Using fault and fold trends Olgers (1969b) has suggested that the Drummond Basin sediments have been compressed by a westerly moving block. The inferred zones of foliation (Saint Anns Megashear and Copperfield Megashear) are shown in Figure 3.

Several points regarding mapped faults are worth noting at this stage. Firstly faults are usually mapped from geological evidence obtained at the surface or from seismic exploration information obtained at depths up to several kilometres. Although some earthquakes do occur at shallow depths (1 to 2 kilometres) the majority would originate from mid-crustal depths (10 to 20 kilometres). Secondly, most interpreted faults were formed in the Palaeozoic and Mesozoic eras over a hundred million years ago. Although these faults can be rejuvenated they frequently represent stress regimes that have long since altered.

Thus any attempt to correlate seismicity with mapped faults is hindered by the effects of scale (mapped faults being at best only a surface expression, in relatively unconsolidated materials, of a larger deep-seated process) and time (mapped faults often representing previous stress regimes).

HISTORICAL SEISMICITY

Prior to the establishment of a seismograph at Charters Towers in 1957, earthquake data were obtained via felt reports or from readings at other seismographs in Australia and the nearby South Pacific islands. After 1957 more local events were recorded but these could not be located unless felt information was obtained or, in the case of larger events, arrival time information from other seismographs was used.

A preliminary report on the seismicity of northeast Queensland with particular reference to the proposed Burdekin Falls damsite (Rynn, 1980) lists 5 events as

being located in the area under discussion. These events are plotted in Figure 4. No attempt has been made to indicate the magnitude of the events in Figure 4, except for the aftershock of the event in 1978 which was smaller than the main shock. Location errors for these events are likely to be large because they were located using only distant seismographs or in other cases only isolated felt reports.

At least 10 other earthquakes have occurred in the area since 1957 (Rynn, 1980). These events were recorded by the seismograph at Charters Towers but could not be located because they were not recorded on any other seismographs or felt by any of the local population.

Other events have also been located (using felt reports) outside the area of interest at Mackay, Ingham, Innisfail and Cairns (Rynn, 1981). Seismic, geomorphic and structural data are currently being used to ascertain the tectonic state of northeast Queensland in Rynn & Heidecker (in preparation).

INSTRUMENTATION

NETWORK

Three Sprengnether MEQ-800 smoked-paper recorders were installed in the Burdekin Falls area in February 1981. Instrument characteristics are listed in Table 2 and the site locations shown in Figures 5 and 6. Originally it was planned to position the three instruments in a network so as to enclose the area of interest (the area of inundation). This proved impossible due to the poor access when the rivers were in flood as well as the extra equipment needed to operate the instruments separately.

For an area to be adequately monitored it should be situated within a seismograph network. For this reason serious consideration should be given to extending the existing network to cover the entire area that is of interest to this project. This point will be discussed further in the final chapter.

The network has not been enlarged to date for two reasons; firstly, once a network is installed it is advisable not to alter it for a suitable period so that the seismicity can be studied without any changes in instrumentation; if any changes in seismicity are observed when a network is altered then it would be hard to ascertain whether the change was in fact real or due simply to the difference in instrumental coverage. Secondly, the current network seems to be fulfilling the role for which it was

intended - that is to obtain an idea of the natural seismicity in the vicinity of the proposed dam.

RECORDERS

The installation consists of two components - a seismometer which is buried in the ground, and a recording instrument which is housed in a wooden box about 5 to 10 metres away from the seismometer. The seismometer converts the ground motion into an electric signal which is transmitted via a cable to the recording instrument where it is amplified and used to drive a stylus on a smoked paper record. The maximum magnification of ground motion is almost 500 000 for frequencies around 10 Hz.

As well as the stylus moving in one direction in response to the ground motion the paper moves at right-angles at a constant rate (1 mm/s) so that the arrival times of various seismic phases can be obtained. Timing marks (12 hours, hours, minutes and seconds) are automatically applied to the record via an internal crystal clock. A radio time signal is used as an absolute time reference to correct for any drift in the internal clock. This radio signal is applied to the record, and the internal clock synchronised, every time the record is changed (every 4 days). Internal clock drifts are less than 0.02 s/day.

Accurate timing is essential in a seismic network of this size. An accuracy of about 0.02 s in arrival times for impulsive first arrivals is being achieved at Burdekin - by lightly smoking the records so that a very fine trace is produced; by recording accurate clock corrections at the start and end of each record; and by recording second marks on the records so that a microscope can be used for interpolating the arrival time.

OPERATIONS

In the 16 months of network operation to date there has been very little down-time of the instruments. A major disadvantage of the current network is the significant time-delay between when an instrument malfunctions to when it is repaired. Because the officers operating the instruments are not fully trained to detect irregularities, faults are often not discovered until the records arrive in Brisbane up to 2 weeks later. Added to this is the time taken to determine the fault, to contact the damsite and to remedy the situation.

The only major problem regarding noise levels on the records is that the Glendon Crossing site being close to the Falls is noisy when the river is in flood. During

these periods the amplifier gain is reduced. During storms thunder is exhibited on the records as high frequency noise. This phenomena is of little concern to the network because it usually affects only one site at a time for a relatively short duration.

DATA ANALYSIS

ROUTINE ANALYSIS

Records are regularly sent to Brisbane where they are annotated and read. Reading involves listing all observed events with the time of arrival to the previous minute together with a code for identifications. This code classifies the event into a teleseism (distance greater than 1000 km), regional earthquake (300-1000 km), local earthquake (0-300 km), microearthquake (magnitude less than 1.0) or blast.

BLAST IDENTIFICATION

Any event that is possibly a blast is compared with tracings of definite blasts from the various coal mines and quarries. In this manner at least 70% of all possible blasts are attributed to a particular quarry with reasonable certainty, with a further 20% being attributed but with less certainty. The remaining 10% are events that cannot be definitely ascribed to any particular quarry but which are most probably blasts. This is usually due to the blast being of small amplitude on the seismograms or the records being noisy.

Any events that are obviously blasts but which cannot be correlated are immediately located (see following section on location procedures). The event is usually located near a quarry or coal mine which is then contacted to confirm that blasting is in fact being carried out. The primary aim is to keep up to date with record reading so that new blasting centres, or centres that are only blasting for a limited period, are quickly identified and contacted.

Any events that could possibly be earthquakes are located and then classified as either a questionable blast or an earthquake. This decision is based on the location, time of day, day of week and signal characteristics (such as frequency content, relative S-wave amplitude, presence or absence of surface waves) of the event. It is hoped that with the above routine there are no earthquakes that have been classified as blasts and no blasts that have classified as earthquakes. Most, if not all events listed as

questionable blasts are undoubtedly blasts that for some reason cannot be attribued to a particular shotpoint (usually because of a poor location).

LOCATION PROCEDURES

The location program currently being used is one that has been copied from the Seismology Centre at the Phillip Institute of Technology in Melbourne. This program was modified slightly in order that it could be run on the PDP-10 at the University of Queensland.

The seismograms of an event that is to be located are re-read to obtain accurate arrival times of the various seismic phases, first motion directions and record durations. About 30% of the events of interest are recorded on the seismograph at Charters Towers which is operated by the University of Queensland. Records from this station are read and the relevant information recorded.

Arrival times are entered into the locating program and a manually controlled iterative procedure produces a "best fit" solution. This solution will not be the actual earthquake (or blast) location because there are several errors involved in the process.

The most obvious source of error is due to inaccuracies in timing. Errors in arrival times of impulsive first arrivals are very small (about 0.02 s) but for emergent or later arrivals the errors could be as high as 0.5 second. Timing errors can also be introduced via the misidentification of a seismic phase. This can either occur with the reading of a later arrival or with the reading of a very small and emergent first arrival.

Another error inherent in any earthquake location is due to the crustal model that is used by the locating program. A model that represents the velocity of the crust at various depths (see following section) is used by the computer to calculate theoretical travel times. These travel times are then compared with the observed travel times and the event location altered so that the differences between the two sets of times is minimised. Any errors in the crustal model will automatically be transferred to errors in the computer location.

The effect of the errors mentioned above on the final location accuracy is controlled by the size and configuration of the seismograph network and by the earthquake location in relation to that network. For an event outside the locating network any error in either the timing or the crustal model will be magnified to give

large location errors. For events inside a network this effect is minimised and event locations should be more accurate. It is for this reason that to properly study an area the monitoring network should, if possible, entirely cover that area.

CRUSTAL MODEL

The crustal model currently being used is based on the models derived by Finlayson (1968) and Cull & Riesz (1972). Although these two studies showed some degree of uncertainty and inconsistency (Dooley, 1980) they are the studies that have been conducted closest to the area under investigation. Alterations to the model were made on the basis of the apparent velocities of the arrivals at Charters Towers and the Burdekin Falls network from various shot-points. The field work for a profile transecting the reservoir area was carried out in mid-1981 by the University of Queensland but this data has not yet been analysed.

The recording of some different shot-points and the subsequent re-analysis of some old recordings has suggested several improvements that can be made to the model. In order to obtain more accurate or realistic event locations more work needs to be done in the area of crustal modelling.

MAGNITUDE CALCULATION

The original M_L (Local magnitude) scale (Richter, 1958) was based on earthquakes occurring in Southern California that were recorded on a specific type of seismograph. Since then the scale has been used in many parts of the world with various amendments to account for different crustal structures and different recording instruments. A duration based magnitude, M_D, is now in common use in local seismicity studies because of its ease in determination. M_D is generally defined to be equivalent to M_L.

The M_D magnitudes for this study were calculated using a formula derived by Cuthbertson (1977) in Victoria. No attempt has been made to adapt the scale to this region of Queensland (the same type of instruments are being used in each study) and this is another aspect of the project that will need further study. The current method is considered to be quite adequate for a preliminary investigation.

DATA PRESENTATION

Once an event has been located the relevant information is entered onto a computer file. This file is a chronological list of all the located events, with the data,

time, location, location errors and magnitude of each event. Other information, such as the number of arrivals used in the location, date of location, locating program, crustal model, and place name is also included as well as codes for the event type and location accuracy. Events of interest that have been recorded and cannot be located (because they were only recorded on one station) are also entered with certain columns left blank. For a full description of the codes used see Appendix I.

A program has been written to handle this data file. Events can be "masked" depending on location accuracy, event type or magnitude. Events can also be grouped according to their location. Output from these procedures consists of a printed output (with either geographic or AMG co-ordinates) and a location plot (with various symbol options).

RESULTS

GENERAL

In the $16\frac{1}{2}$ months of monitoring to the end of July 1982 almost 2000 events have been recorded and noted as described in the Routine Analysis section of the chapter on Data Analysis. Of these about 12% have been identified as teleseisms (distances greater than 1000 km) with only 3% being earthquakes of local (0-300 km) or regional (300-1000 km) origin. The remaining 85% have been identified as blasts from the various local quarries and from coal mines up to 550 km away.

Of these 2000 events, 113 events have been located and the information entered onto a computer file (described in previous chapter). This file of located events includes all recorded earthquakes as well as some interesting, unusual or previously unidentified blasts. Henceforth, the discussion will be entirely concerned with this computer file of located events.

BLAST LOCATIONS

Figure 5 is a plot of events that are on the computer file that have been located and identified as either blasts or questionable blasts. The various shot points in the area are also plotted in Figure 5. Many of these events have been definitely correlated with blasts listed on the logs supplied by the various quarries. Other events that have not been correlated with logged blasts (usually due to the logs being unavailable or non-existant) can in most cases be assumed to originate from a particular

quarry due to their proximity to other identified blasts. In this manner the blasts from each blasting centre (or group of blasting centres) have been grouped and labelled with only one event being unidentified.

The spread in locations of blasts from a single blasting centre gives an indication of the location accuracy of the current network although several points should be noted in this regard. Firstly, many of these blasts (especially from the Townsville area and Newlands) have been recorded as very small events making accurate timing difficult. Secondly, blasts have relatively weak S (Shear)-waves as compared to earthquakes. These waves are most important if an accurate location is required. Finally, a lot of locations differ systematically from the actual blasting centres (for example Goonyella, Newlands, Bowen area). This systematic deviation is indicative of a location problem due to an incorrect crustal model. As indicated in the previous chapter there are several improvements that can be made to the model which should reduce the location errors.

EARTHQUAKE LOCATIONS

All events, excluding blasts and questionable blasts are plotted in Figure 6. The size of the plotted symbols indicates the magnitudes as shown in the legend. Perhaps the most interesting events are the events about 20 km northeast of the damsite which occurred in a 28 day period in October and November, 1981. Eleven events ranging in magnitude from MD -0.4 to 2.5 were located in a small (1 km square) area.

Another notable feature is the group of events located in the Collinsville area about 70 km east of the damsite. Careful checking of lists supplied by the mining company of blasts in the open cut coal mine at Collinsville has ensured that these events are natural in origin. As has been discovered with the Ipswich coal mines using the Wivenhoe Dam Seismic network, large underground collapses can be recorded on seismographs at distances up to tens, or even hundreds of kilometres. At present this aspect is being investigated to see if, in fact, collapses are being recorded. However, the events plotted in Figure 6 are of such a nature that it seems certain they are natural earth-tremors and not blasts or collapses.

The other activity that has been recorded is seemingly randomly scattered. The activity in the northeast part of the map, off the coast of Ayr, is connected with a group of events that extends further offshore. Using the limited data presently available, this area seems to be the most active area of the region currently being monitored.

These results, being drawn from a relatively short period, are only preliminary. Several analyses, such as magnitude and depth distributions and focal mechanisms have not been presented here due to the inaccuracy and paucity of the data. In order to make more conclusive deductions regarding the seismo-tectonics of the area many more events will need to be recorded and located. In general the horizontal errors in locations are too large to allow correlation of events with particular faults.

Improving the crustal model and upgrading the network (see next chapter) would reduce location errors. This should then allow the correlation of events with faults (if any such correlation exists) and the production of a composite focal mechanism plot which would give an indication of the current stress field.

PROPOSALS

AREA OF INTEREST

Siting of the currently operating network was mainly limited by accessability. Flooding of the major streams and rivers of the area made a larger network impractical at the time of installation. As mentioned previously it is necessary to position seismographs so as to enclose the area under study, in order that events in the area can be accurately located.

There is no established convention used to define the area to be considered when investigating the seismic effect of water loading. A common empirical criterion for the definition of influence of a crustal load is that area equal to the loaded area plus one load dimension, that is, select a simple shape for the impounded area and then double the axes with the centre remaining at the reservoir centre. For the proposed Burdekin Falls dam if one ignores the relatively shallow upper reaches of the reservoir then the reservoir can be simplified to a rough parallelogram shape. Doubling the dimensions of this shape gives the "area of interest" shown in Figure 7.

The area included in Figures 1 to 6 is much larger than the area that is of direct interest to the Burdekin Falls dam project. This was due mainly to the fact that discussion of a smaller area would have significantly reduced the amount of data that could have been presented. Coupled with this is the fact that presentation of the data at any scale larger than that given would become meaningless owing to the large errors in locations.

NUMBER OF INSTRUMENTS

To locate events in the area of interest shown in Figure 7 would require a minimum of three seismographs to be situated so as to enclose the area. However in this case the station spacing would be too large. To accurately locate an event (vertically as well as horizontally) the distance from the closest station to the epicentre must be less than the focal depth. It follows that to accurately locate an event of depth d, requires a station spacing s, of less than 2d. To cover an area A, with stations at an average spacing of s=2d, will require a network of A/s^2 or at least $A/4d^2$ stations. For the area shown in Figure 7 (A = 40 km x 60 km), assuming a focal depth of 10 km, this calculation indicates that a network of at least 6 stations is required. These calculations, although only approximations, indicate that to adequately monitor the future impounded area the current network needs to be substantially upgraded.

NETWORK CONFIGURATION

A possible configuration of these instruments is shown in Figure 7. This configuration, although basically illustrative, considers available access and manpower, and network geometry.

An extra station has been proposed north of Collinsville in order that any events that occur in the region but outside the area of interest can be located. The siting of this station north of Collinsville would form a larger network when one considers the proposed network and the University of Queensland station at Charters Towers. This site was chosen also in light of the activity around Collinsville and the swarm of events downstream from the damsite. The accurate location of events outside the area of interest will enable a quicker and more accurate picture of the tectonic setting of the area than would be available by studying events solely from within the smaller network.

EQUIPMENT

The proposed network will either have to be operated by station owners or QWRC personnel from the damsite, or telemetred to some central location.

If analogue recorders, identical to the ones currently in use, are employed at each new station they will require servicing every 4 days. The large distances involved in a round trip from the damsite, especially during the wet season when river crossings are impossible, virtually rules out QWRC personnel from regular (twice weekly) services.

The use of local manpower is a possibility but this would mean far from optimum running conditions due to unskilled operation.

The need for frequent visits to each site would be alleviated if the data were telemetred to a central recording location where it would all be recorded on the one analogue record. The remote sites would then only have to be visited to check batteries and perform routine maintenance perhaps twice a year. Data would be telemetred via UHF radio links owing to the fact that land lines could not be guaranteed in the event of a large earthquake. An advantage of central recording is that activity in the area can be observed virtually in real time, by the personnel operating the facility. However, the records would still have to be sent to Brisbane to determine the location, magnitude etc of any large events.

Telemetry would also enable the data to be recorded digitally. The large volume of data produced by continuous digital recording means that selective recording of events is advisable. This is achieved via a continuous delay memory with a detection algorithm that triggers when an event occurs. The delay memory enables the beginning of the event to be recorded. Digital recording introduces a large dynamic range so that events ranging in size from microearthquakes to larger magnitude events can usually be recorded without distortion. Digital recording also enables more sophisticated analyses than are possible with permanent analogue records. Filtering of noise, signal enhancement, Fourier analysis, and automatic arrival time picking are all possible with digital recording.

A third system to consider is a field based, triggered digital system. Each station would have a delay memory and a triggering circuit which would record events on a cassette. Local personnel could then change cassettes and batteries on a fortnightly basis with a visit by QWRC personnel perhaps once every two months to do calibration and timing tests and maintenance. Unskilled operators would have little trouble performing routine services because the sophisticated equipment can double check and warn the operator if a mistake has been made.

Because the triggering algorithm can never trigger on very small events without triggering on numerous noise signals it is important to complement a digital network with several continuous analogue recorders. The recorders of the current network could be repositioned so that small events in the area that did not trigger any digitals could still be located from analogue records. One recorder could be positioned so that QWRC personnel could service it regularly. In this manner a close watch could be kept on local activity and in the event of an important earthquake the digital tapes

could be collected in a special trip and sent to Brisbane. This procedure would not be much slower than with the telemetry system. One other recorder could be located, together with a digital recorder, at the other end of the network surrounding the reservoir (Fig. 7). The third analogue recorder would be used at the proposed site north of Collinsville. Actual positioning of these analogue instruments will probably depend on finding the locals with the appropriate aptitude and willingness.

The advantage of on-site digital recording over the digital recording of a telementred signal is that the dynamic range is not restricted by the telemetry system. The dynamic range of 108 dB that is available on some triggered digital recorders enables the instruments to operate as strong-motion recorders.

Triaxial (3-component) recordings are relatively simple to implement with triggered digitals. This would be extremely useful in identifying later phases as well as making any focal mechanism solutions more reliable.

In summary it is strongly recommended that digital recording be employed in any upgraded network that is installed. This would enable some sophisticated and accurate analyses to be performed. Field recording is preferred over telemetry because of the ease of installation, the greater dynamic range available and the inherent flexibility.

Any upgrading of the network should be carried out as soon as possible so that a reasonable period of "baseline" of natural activity can be recorded. It would be inadvisable to install a new network at a time when the reservoir is about to be filled because any change in activity could be related to either the reservoir or to the increased sensitivity of the new network.

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Table 1: Historical Earthquakes Located in the Area

Date	Time (GMT)	Latitude (°S)	Longitude (°E)	Magnitude M or Intensity MM	Reference
1913 Dec 18	1354	20.0	147.0	M4	Gutenberg & Richter (1954)
1963 Feb 12 ?	1602	('Brittania Downs' Station)		MMIII	Rynn (1980)
1977 Sept 23	1531	('Trafalgar' Station)		MMIII	Rynn (1980)
1978 May 24	1737	20.6	146.8	MMIV	Rynn (1980)
May 24	2345	20.6	146.8	(Aftershock)	Rynn (1980)

Table 2: Instrument Characteristics

Site Name	Code	Latitude (°S)	Longitude (°E)	AMG Zone	Northing	Easting	Height (m)	Start Date	Maximum Magnification	Foundation
Glendon Crossing	BFGC	20.6140	147.1609	55	7720.557	516.768	160	81/02/12	460K @ 13Hz	Andesitic lithic tuff
Mt Graham	BFMG	20.6142	147.0608	55	7720.538	506.337	160	81/02/13	460K @ 13Hz	Rhyolitic tuff
Glenroy Station	BFGR	20.5492	147.1052	55	7727.732	510.966	160	81/02/16	460K @ 13Hz	Conglomerate

Table 3: Earthquakes Located with the Burdekin Falls Network

(February, 1981 to June, 1982)

Date	Time (UTC)	Lat. (°S)	Long. (°E)	Depth (km)	Mag.	Accuracy	Type	Place
81/02/15	1939	19.226	147.748	7.6	MD 1.0	E		Off Ayr
81/03/11	0716	19.073	147.546	10.0	MD 1.8	F		Off Ayr
81/03/21	0813	20.203	146.485	0.0	MD 2.7	D		SE of Charters Towers
81/05/22	1013	20.728	147.033	0.0	MD 0.5	C	U	Mt McConnell
81/05/22	1200	20.733	147.038	0.0	MD-1.0	E	U	Mt McConnell
81/06/04	0359	20.781	146.764	10.0	MD 0.8	M	U	Harvest Home
81/06/28	2141	20.737	146.288	16.7	MD 2.0	C		Mt Bellevue
81/07/04	1343	20.222	147.627	8.7	MD 0.7	C	U	Capsize Creek
81/07/10	1544	20.819	147.899	14.3	MD 1.2	B		Mt St Martin
81/07/14	2229	21.085	146.724	14.3	MD 1.0	C	S	Scartwater
81/07/14	2229	21.106	146.754	10.8	MD 1.3	C	S	Scartwater
81/07/14	2231	21.072	146.720	18.2	MD 1.0	B	S	Scartwater
81/07/18	0058	20.220	147.632	0.0	MD 0.5	C	U	Capsize Creek
81/07/20	2153	20.799	147.964	14.0	MD 1.0	B		Mt St Martin
81/08/13	0634	20.439	147.758	0.0	MD 1.8	C		Collinsville
81/08/31	0601	20.528	148.168	8.2	MD 1.5	C		Mt Roundback

Table 3 (continued)

Date	Time (UTC)	Lat. (°S)	Long. (°E)	Depth (km)	Mag.	Accuracy	Type	Place
81/09/10	1158	20.511	147.682	0.0	MD 1.0	C		Mt Bella Vista
81/09/10	1159	20.523	147.686	8.4	MD 0.9	C	U	Mt Bella Vista
81/09/12	1849	20.477	147.853	0.0	MD 0.8	E	U	Collinsville
81/10/03	1627	20.500	147.705	20.6	MD 0.5	E	U	Mt Bella Vista
81/10/03	1818	20.516	147.733	13.9	MD 0.9	C	U	Mt Bella Vista
81/10/03	1818	20.477	147.718	16.6	MD 0.9	B	U	Mt Bella Vista
81/10/08	0339	20.464	147.260	0.0	MD 1.7	C		Leichardt Weir
81/10/08	2142	20.464	147.263	0.0	MD 0.2	C	U	Leichardt Weir
81/10/09	0008	20.513	147.746	0.0	MD 0.4	D	U	Mt Bella Vista
81/10/11	1002	20.464	147.267	0.0	MD 2.5	C		Leichardt Weir
81/10/11	1126	20.462	147.256	0.0	MD-0.4	C	U	Leichardt Weir
81/10/11	1741	20.464	147.262	0.0	MD-0.2	C	U	Leichardt Weir
81/10/12	0711	20.467	147.259	0.0	MD 1.6	C		Leichardt Weir
81/10/12	1921	20.464	147.257	0.0	MD 0.3	C	U	Leichardt Weir
81/10/26	2335	20.467	147.263	1.7	MD 1.0	C		Leichardt Weir
81/10/29	0601	20.215	147.670	13.0	MD 0.6	B	U	Capsize Creek
81/10/29	1717	20.464	147.263	2.7	MD 0.4	C	U	Leichardt Weir
81/11/01	1136	20.466	147.265	0.0	MD-0.4	C	U	Leichardt Weir

Table 3 (continued)

Date	Time (UTC)	Lat. (°S)	Long. (°E)	Depth (km)	Mag.	Accuracy	Type	Place
81/11/05	1112	20.465	147.263	0.0	MD 0.9	D	U	Leichardt Weir
82/01/27	1624	19.350	148.219	10.0	MD 1.7	F		Off Ayr
82/02/21	1757	21.504	147.492	0.0	MD 1.2	F		Mt Coolon
82/03/01	1930	20.993	146.031	15.3	MD 1.3	D		Egera Station
82/03/09	0939	21.089	147.882	10.0	MD 0.8	M	U	Newlands area
82/06/10	0846	20.430	146.730	0.0	MD 1.5	D		Mt Cooper

Figure 1

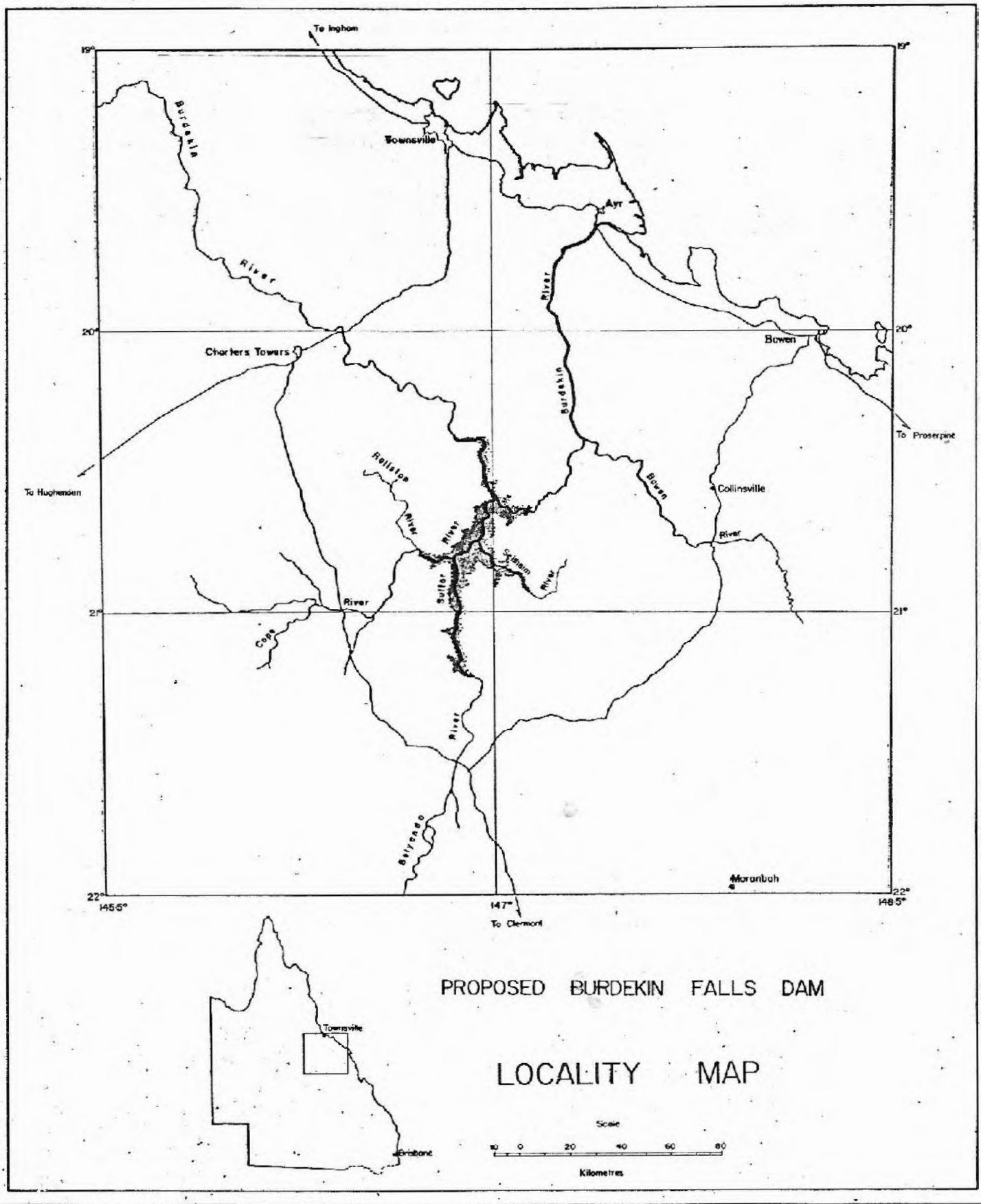
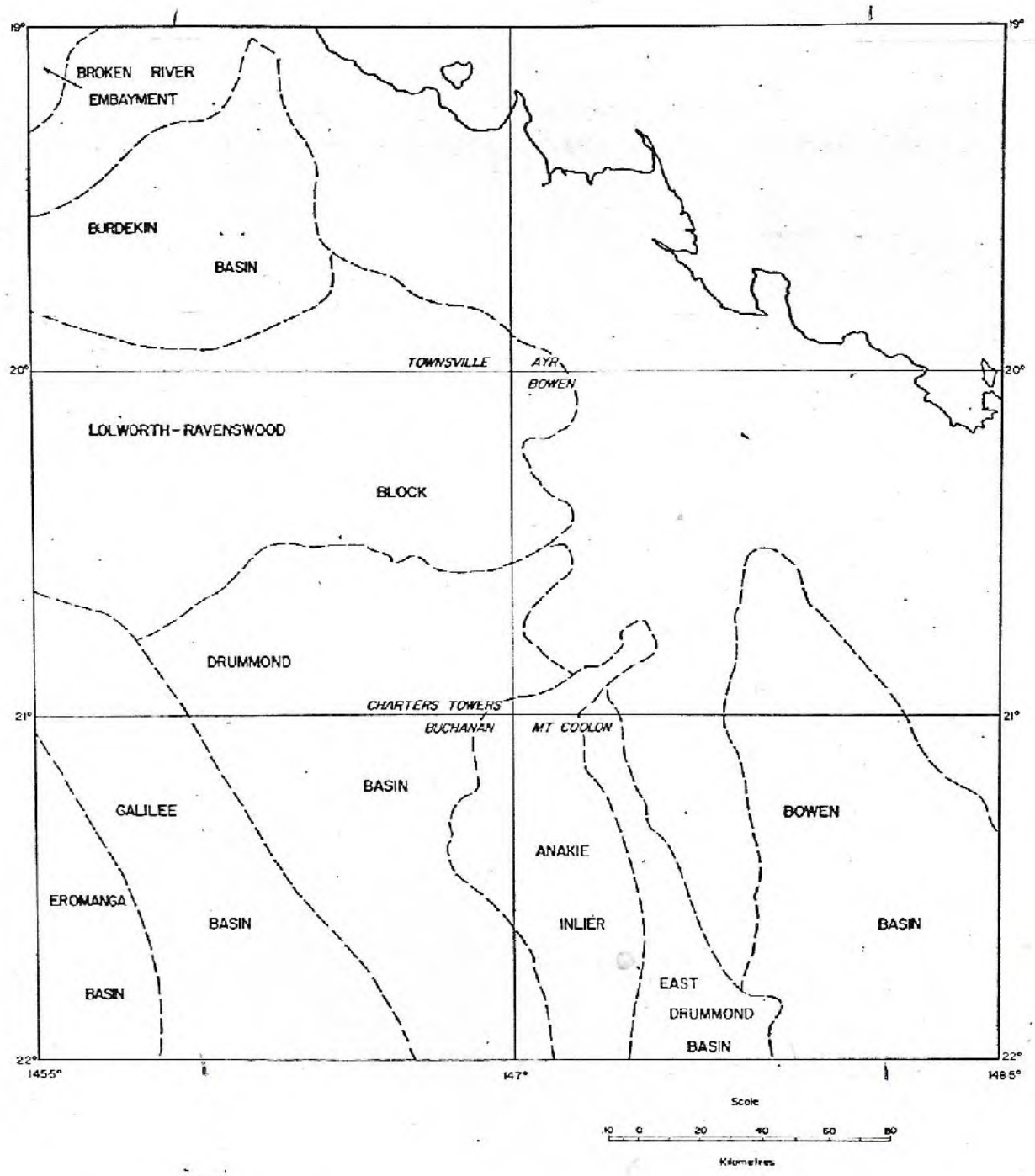

To Ingham
Townsville
Burdekin River
Ayr
Charters Towers
Bowen
To Proserpine
To Hughenden
Collinsville
Belyando River
Suttor River
Cape River
Moranbah
To Clermont
19°
20°
21°
22°
145°
147°
148°
Townsville
Brisbane
PROPOSED BURDEKIN FALLS DAM
LOCALITY MAP
Scale
0 20 40 60 80
Kilometres

Figure 2



Note

Unnamed Areas : Mesozoic & Late Palaeozoic Volcanics and Intrusives

MAJOR STRUCTURAL UNITS

Figure 3

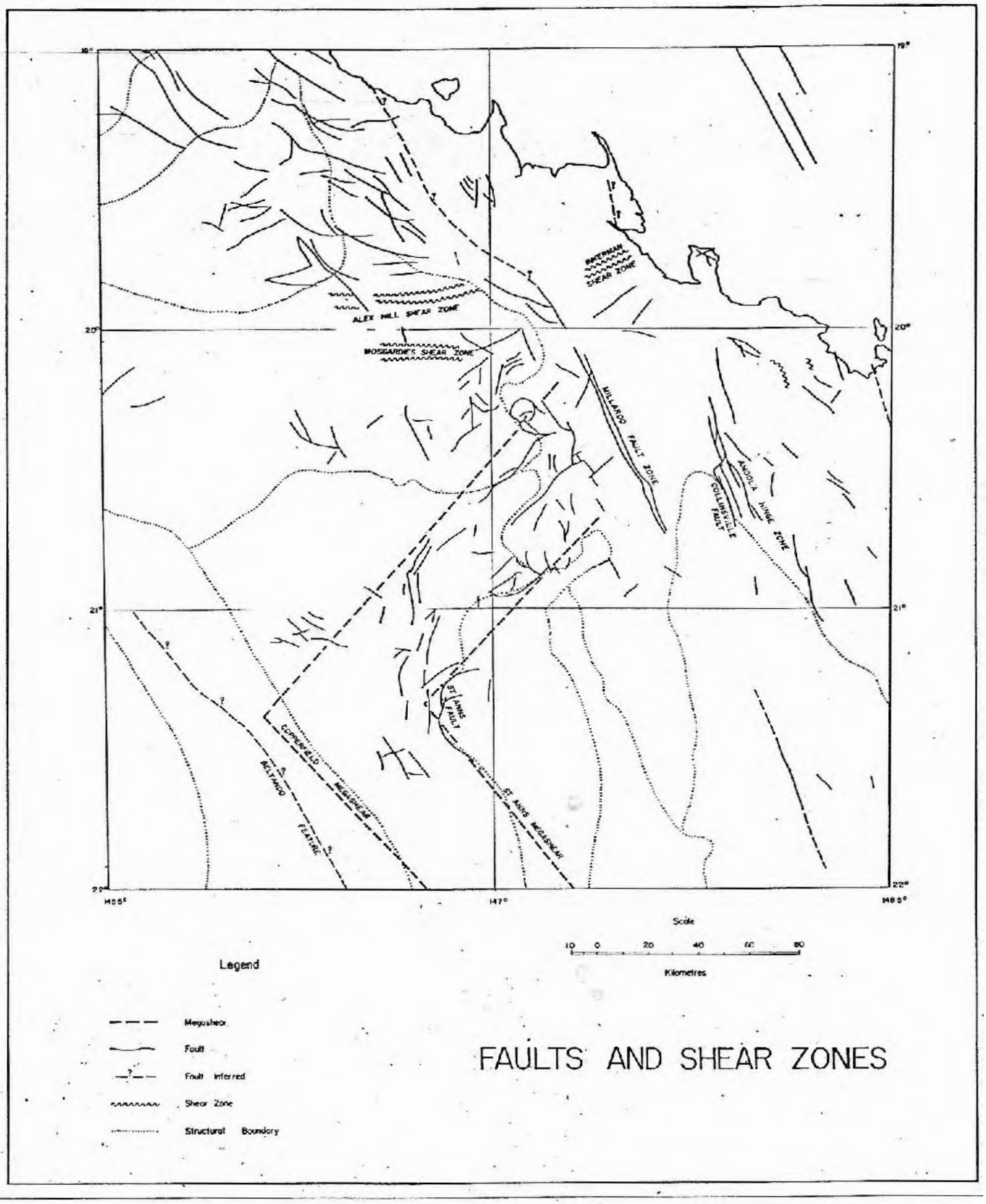
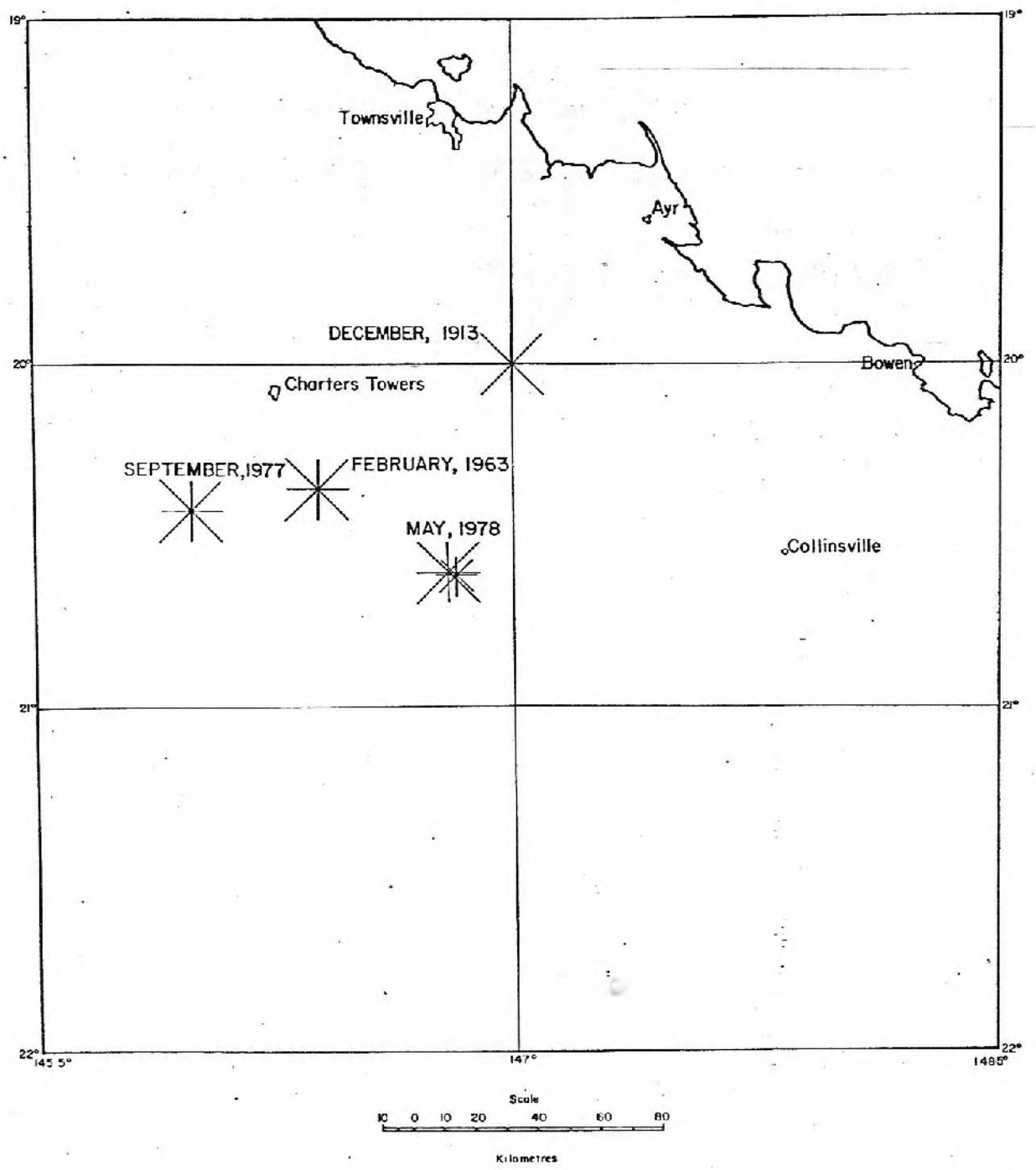

19°
20°
21°
22°
145°
147°
148.5°
ALEX HILL SHEAR ZONE
BOSSARDIES SHEAR ZONE
BAYNHAM SHEAR ZONE
MILLAROO FAULT ZONE
COLLINSVILLE FAULT
ANGOLA HINGE ZONE
ST ANNS FAULT
COPPERFIELD MEGASHEAR
ST ANNS MEGASHEAR
BELYANDO FEATURE
Scale
10 0 20 40 60 80
Kilometres
Legend
Megashear
Fault
Fault Inferred
Shear Zone
Structural Boundary
FAULTS AND SHEAR ZONES

Figure 4



HISTORICAL SEISMICITY

Figure 5

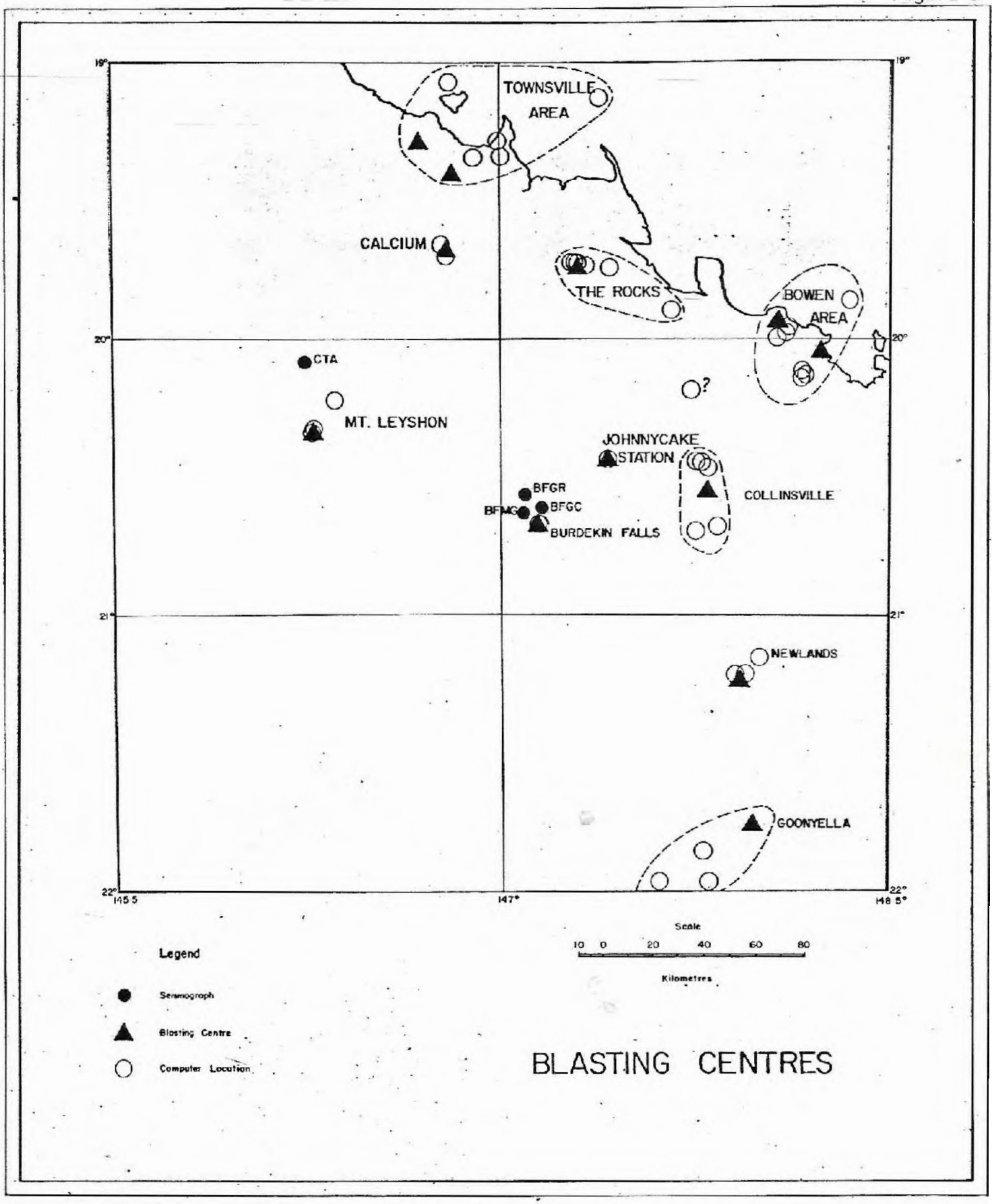

19°
TOWNSVILLE
AREA
CALCIUM
THE ROCKS
BOWEN
AREA
20°
CTA
MT. LEYSHON
?
JOHNNYCAKE
STATION
BFGR
BFMG
BFGC
BURDEKIN FALLS
COLLINSVILLE
21°
NEWLANDS
GOONYELLA
22°
145 5
147°
148 5°
Scale
10 0 20 40 60 80
Kilometres
Legend
Seismograph
Blasting Centre
Computer Location
BLASTING CENTRES

Figure 6

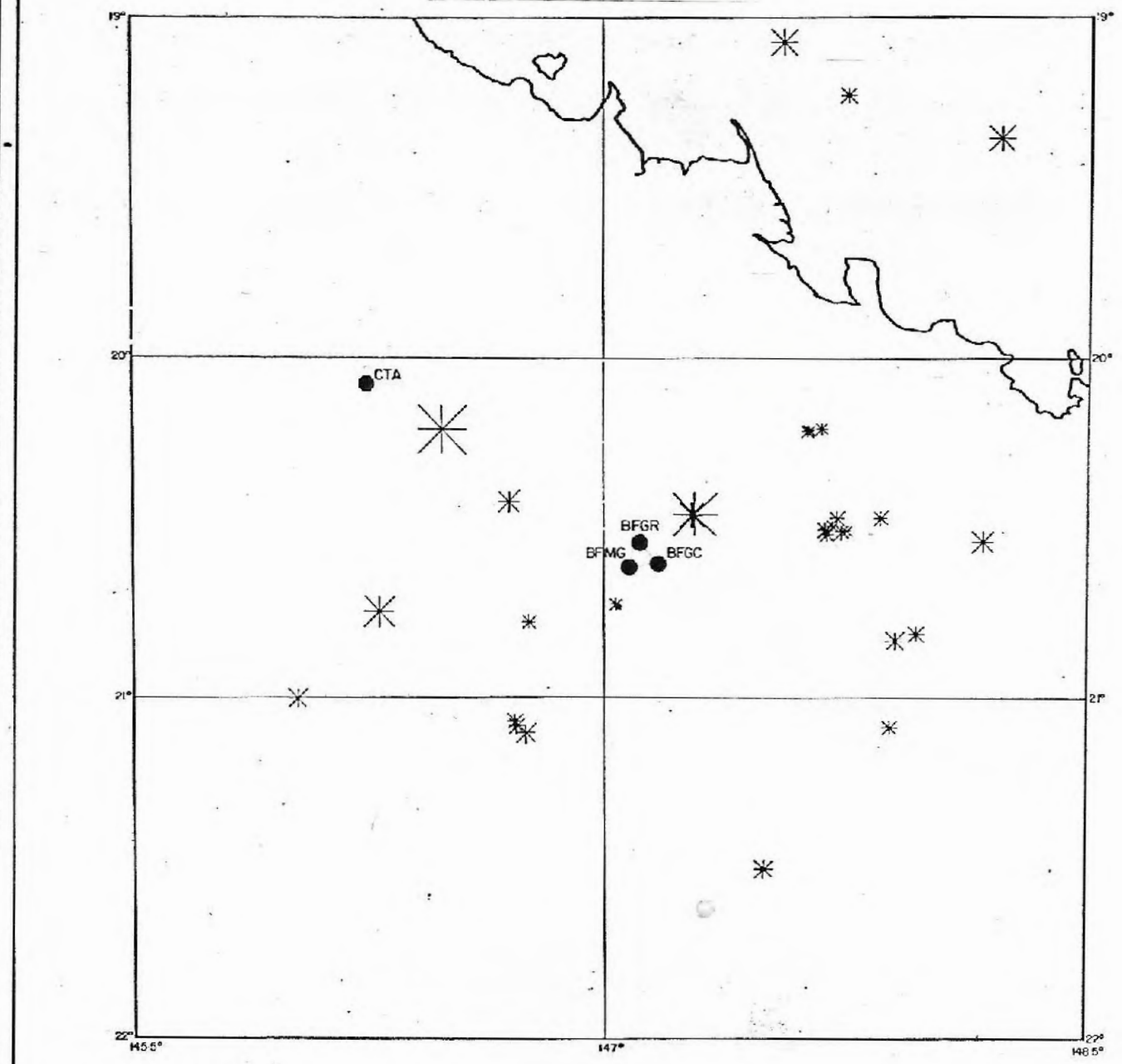
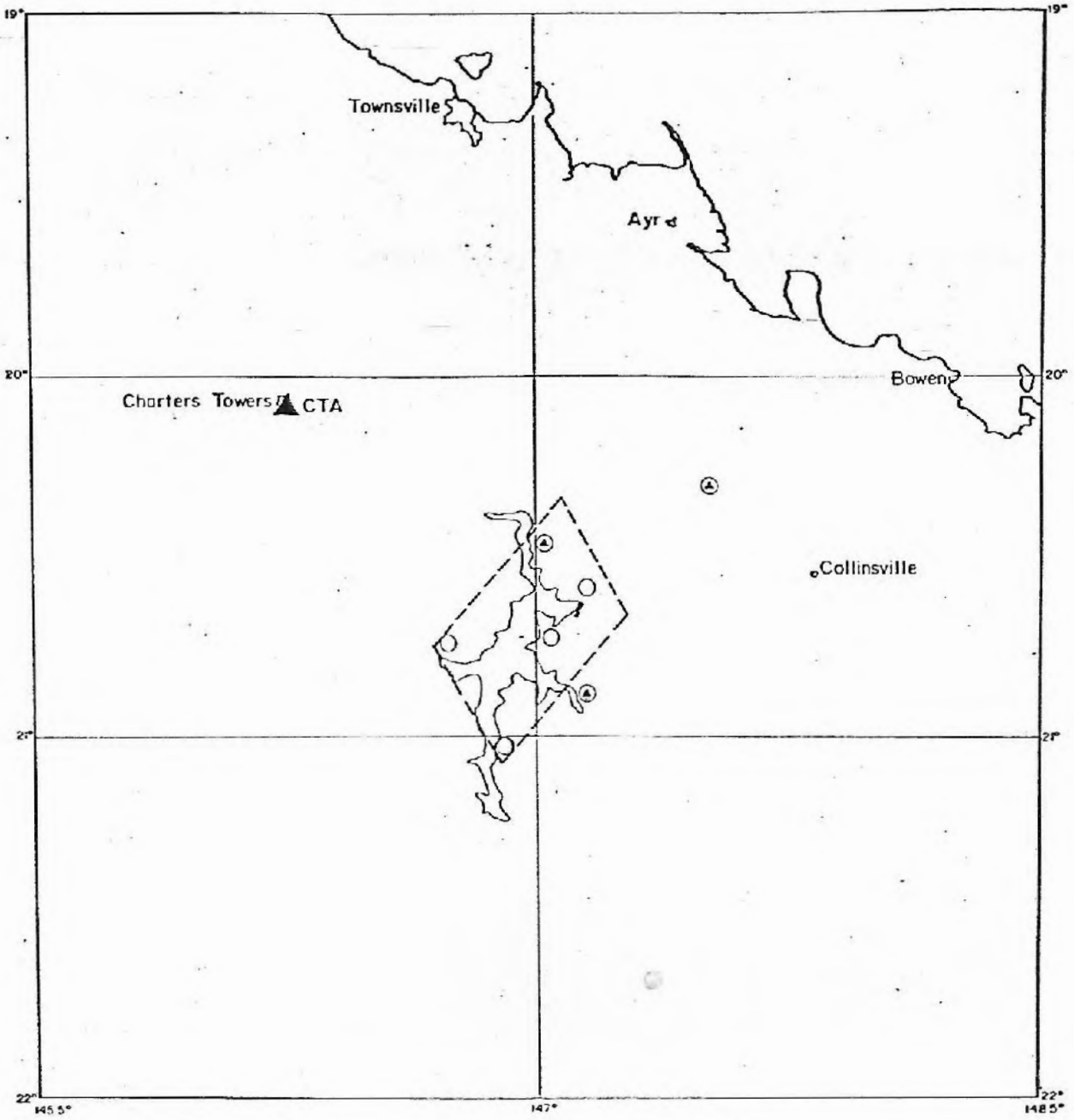

19°
19°
20°
20°
CTA
BFGR
BFMG
BFGC
21°
21°
22°
22°
145.5°
147°
148.5°
Magnitude
3·0
2·0
1·0
0·0
Legend
Seismograph
Scale
10 0 20 40 60 80
Kilometres
EARTHQUAKES LOCATED WITH BURDEKIN FALLS NETWORK

Figure 7



Legend

"Area of interest"

Triggered digital seismograph

Analogue seismograph

Existing seismograph
(Operated by University of Queensland)

Scale

10 0 20 40 60 80

Kilometres

PROPOSED NETWORK

APPENDIX 1: FORMAT AND CODING OF COMPUTER FILE

Events are filed on a sequentially accessed ASCII file, one event per record. The format for each record is:-

Column	Format	Explanation	Example
1-6	312	Date (Year, Month, Day)	810512
7-10	212	Origin time (hours, minutes-GMT)	0940
11-15	F5.2	Origin time (seconds)	45.18
16-22	F7.4	Latitude (degrees south)	19.8406
23-30	F8.4	Longitude (degrees east)	148.3331
31-32	12	AMG zone	55
33-39	F7.2	Northing (AMG in kilometres)	7805.6
40-45	F6.2	Easting (AMG in kilometres)	639.6
46-50	F5.2	Depth (in kilometres)	10.00
51-54	F4.	Location error - N-S (in km)	5.67
55-58	F4.	Location error - E-W (in km)	2.39
59-62	F4.	Location error - Depth (in km)	10.5
63-66	F4.	Location error - Time (in seconds)	0.40
67-68	I2	Number of arrival times	6
69-72	F4.3	Standard deviation of arrival times	.083
73-74	A2	Magnitude type	MD
75-78	F4.1	Magnitude value	1.7
79	A1	Maximum intensity (only if felt)	
80	A1	Location accuracy code (see following)	E
81-82	A2	Event type code (see following)	B?
83-84	I2	Location run number	2
85-90	I6	Date of location run (YYMMDD)	810601
91-99	A5, A4	Location program name and version	EQLOC3.1
100-103	A4	Crustal model code	BFQ1
104-128	5A5	Place name	BOWEN

Location accuracy code (col. 80) is a qualitative measure that depends on the quality of the arrival time data and the position of the earthquake relative to the seismographs. Codes are:-

A Very good epicentre and depth using local crustal model.
B Very good epicentre and depth using a regional crustal model.
C Very good epicentre and good depth.
D Good epicentre, but depth uncertain.
E Fair epicentre, but with no depth control.
F Poor instrumental location.

O Recorded on only one seismograph - Distance less than 10 km.
P Recorded on only one seismograph - Distance between 10 and 50 km.
Q Recorded on only one seismograph - Distance greater than 50 km.

U Unlocatable (not enough arrival time information).
M Mirror solution possible.

Event type is a code to permit a more detailed study of events. Most local earthquakes will be uncoded.

F Foreshock
M Mainshock
A Aftershock
S Member of swarm
U Microearthquake (MD less than 1.0)
B Blast
C Underground collapse
R Regional (300-1 000 km)
T Teleseism (more than 1 000 km)
? Uncertain

Selected information from the file is sorted, formatted and output. Output codes (such as in Table 3) are the same as listed above.