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COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1971/141

013467

A DETAILED SEISMIC STUDY OF GOSSES BLUFF

by

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SUMMARY

The seismic study of Gosses Bluff was part of a comprehensive multidisciplinary investigation of the feature undertaken jointly by the Bureau of Mineral Resources and the United States Geological Survey. The project was aimed at obtaining a better understanding of a structure which is in many ways similar to the craters on the Moon, and also at resolving a long-standing controversy about the origin of Gosses Bluff.

The field seismic survey over a period of five months used single and multiple coverage reflection techniques to obtain high quality data on the Bluff's sub-surface structure. Two radial traverses each about 25km long were surveyed through Gosses Bluff and offset shooting was used to record information from under the inaccessible Bluff walls. Extensive processing by both analogue and digital means has been used to enhance the data.

No reflections were recorded in the immediate vicinity of Gosses Bluff shallower than about 5500m, although good continuous reflections occurred deeper than this. The shape of the zone of disruption has been deduced from the seismic results with the aid of gravity results to be a shallow saucer of diameter 23km and maximum depth 800m superimposed on a roughly hemispherical bowl of diameter 8.6 km and depth 4300 m. The continuity of reflections above the Proterozoic Bitter Springs Formation casts doubt on theories of origin requiring piercement by Bitter Springs salt.

The seismic results are entirely consistent with Gosses Bluff's being a structure formed by the impact of an extra-terrestrial body, that is an astrobleme.

A salt pillow has been shown to exist under Gosses Bluff; it probably developed initially as part of the Gardiner-Tyler Anticline and was later moved upward as a consequence of the impact.

INTRODUCTION

A programme of seismic work was carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR) in the Gosses Bluff area of the Amadeus Basin, Northern Territory, during the period April to August 1969. Gosses Bluff lies in petroleum exploration lease OP 175 held by Magellan Petroleum (NT) Pty Ltd. Exoil Pty Ltd, Transoil NL, and Flinders Petroleum NL hold interests in the Gosses Bluff block of OP 175.

Gosses Bluff, which was discovered by Edmund Gosse in 1873, lies near the northern margin of the Amadeus Basin about 170km west of Alice Springs. It is a prominent circular range with an overall diameter of about 4km and rises about 200m above the general level of the Missionary Plain. The range encircles a pound about 2km in diameter which is only slightly elevated above the level of the outside plain. The single drainage channel through the Bluff walls provides the only vehicular access to the pound.

The seismic survey was part of a combined geological and geophysical investigation of Gosses Bluff undertaken jointly by the BMR and the United States Geological Survey (USGS). The USGS, which undertakes astrogeological studies for the National Aeronautics and Space Administration (NASA), has been studying Gosses Bluff, and other similar structures throughout the world, mainly in order to contribute to a greater understanding of the circular features on the surface of the Moon.

The joint project occupied three years field work: geological mapping in 1967, further mapping and detailed aeromagnetic and gravity coverage in 1968, and, concurrent with the seismic survey in 1969, completion of the gravity work and a brief follow-up ground magnetic survey.

Gosses Bluff, originally thought to be a diapiric structure, was considered by many workers at the time the survey started to have been formed by the impact of an extra-terrestrial body. The seismic survey was intended to define the various structural features of the Bluff more precisely than had been possible from previous investigations and add support or otherwise to the hypothesis that Gosses Bluff is an impact crater.

An operational report on the survey, providing details of staff, equipment, operational statistics, and preliminary results and conclusions at the end of the field survey, has been presented by Brown (1971a). Extensive analogue and digital processing of the seismic data has now been completed and a detailed interpretation has been made. A comprehensive report on the recording, processing, analysis, and interpretation relating to the seismic work at Gosses Bluff is presented here.

GEOLOGY

The geology of the Amadeus Basin has been described in detail by Wells, Forman, Ranford, & Cook (1970). The Amadeus Basin is a structural depression elongated east-west and covering about 200 000km^2 of the southern part of the Northern Territory. An unmetamorphosed sedimentary sequence more than 9000 metres thick is preserved above the Precambrian basement. The basin is bounded by the basement rocks of the Arunta Complex on the north and those of the Musgrave-Mann Complex on the south. The east and west margins are obscured, in the east by younger sediments of the Great Artesian Basin and in the west by the Canning Basin. The structural pattern is mainly of broad, flat-bottomed, asymmetric synclines with narrow anticlines and uplifts complicated by thrust faults and diapirism. Two major orogenic events deformed the basin succession, the Proterozoic Petermann Ranges Orogeny and the Devonian/Carboniferous Alice Springs Orogeny.

Gosses Bluff lies near the western part of the Missionary Syncline between the MacDonnell Ranges on the north and the Gardiner and Krichauff Ranges on the south. The stratigraphy in the MacDonnell Ranges near Gosses Bluff is shown in Table 1.

Two formations in the Amadeus Basin have been found to contain salt: the Proterozoic Bitter Springs Formation and the Cambrian Chandler Limestone. The Bitter Springs Formation has been shown to contribute towards diapirism. Recently Mount Liebig (BMR) No. 1 drill hole (Kennewell, 1971) has penetrated several hundred metres of salt in the Bitter Springs Formation close to Gosses Bluff.

Table 1. Generalized Stratigraphy, Western MacDonnell Ranges

Age		Group	Formations	Approximate Thickness (metres)
CARBONIFEROUS?-DEVONIAN		Pertnjara	Brewer Conglomerate	1500
			Hermannsburg Sandstone	900
			Parke Siltstone	450
DEVONIAN - SILURIAN?			Mereenie Sandstone	600
ORDOVICIAN	Upper	Larapinta	Carmichael Sandstone	150
			Stokes Siltstone	450
	Middle		Stairway Sandstone	450
	Lower		Horn Valley Siltstone	400
			Pacoota Sandstone	600
CAMBRIAN	Upper	Pertaoorrta	Goyder Formation	500
	Middle		Jay Creek Limestone	100
			Hugh River Shale	500
	Lower		Arumbera Sandstone	250
PROTEROZOIC			Pertatataka Formation	650
			Areyonga Formation	400
			Bitter Springs Formation	750
			Heavitree Quartzite	450
ARCHAEAN			Arunta Complex	

The first recorded geological investigation of Gosses Bluff was carried out in 1956 by Prichard & Quinlan (1962). Their opinion, that the structure was of diapiric origin with the Bitter Springs Formation the mobile unit, was supported by McNaughton, Quinlan, Hopkins, & Wells (1966) and gained widespread acceptance.

Brunnschweiler (1959) suggested that the Bluff was formed by the injection of an acid igneous plug which subsequently resisted orogenic movements. However, this postulate was not generally accepted.

In 1964 K.A.W. Crook of the Australian National University recognised a shatter cone in Gosses Bluff. This threw serious doubt on the diapiric hypothesis. Crook & Cook (1966) subsequently showed that Gosses Bluff had many of the features of a crypto-explosive structure. The term 'crypto-explosion' was coined by Dietz (1959) to mean explosion without genetic connotations. Crook & Cook were unable to agree on whether the explosive force was of intra-terrestrial (crypto-volcanic) or extra-terrestrial (astrobleme) origin; but they later agreed that the structure was most probably an astrobleme (Cook, 1966). They estimated the minimum overall diameter to be 16km.

There are two possible versions of the crypto-volcanic hypothesis: a subterranean accumulation of gas may have caused a deep-seated explosion (Crook & Cook, 1966); alternatively, a ball of gas at least 2km in diameter may have accumulated on the surface and been ignited by lightning.

Ranneft (1970) has proposed that Gosses Bluff is a fossil mud volcano. This is another form of diapiric structure involving initially the piercement of several formations by Bitter Springs salt, followed by piercement to the surface by gas carrying mud and rock fragments.

The astrobleme or impact hypothesis, however, was at the start of this study the most generally accepted origin of Gosses Bluff (Glikson, 1969).

Probable impact structures throughout the world have been investigated by Dietz (1961, 1967, 1969), Innes (1961, 1964), and other researchers. Some of the more notable features, such as the Sudbury structure in Canada, the Vredefort Ring in South Africa, and the Ries Crater in Germany, have now been recognized as astroblemes.

The central zone of Gosses Bluff has been mapped in detail by Milton (Milton et al., 1971) and the outer zone by Glikson (1969).

All evidence suggests that Gosses Bluff was formed in a flat-lying sedimentary sequence. However, the present Bluff is composed of beds of Mereenie Sandstone and the basal sandstone of the Pertnjara Group in a vertical or steeply dipping attitude. The beds of the Larapinta Group inside the Bluff also are generally almost vertical and at the centre are seen to form a tight anticline. An exploratory well, Gosses Bluff No. 1 (Pemberton & Planalp, 1965), located in the centre of the structure, was drilled to a total depth of 1382m. The well site was chosen on the assumption that Gosses Bluff was a salt dome; it was in very steeply dipping Larapinta Group sediments throughout and did not encounter salt. There was, however, a gas show.

The rocks of the Larapinta Group in the centre of the Bluff have been raised to the surface from a depth of 3000m or more to form a central uplift. The present topography in the form of a ring is an accident of lithology and is part of the circular pattern of geological units mapped. En echelon faulting in the central uplift indicates crowding that results from displacement not only upward but also inward. This feature has been proposed as a characteristic of impact craters (Wilshire & Howard, 1968). It has been shown experimentally (Roddy, Jones & Diehl, 1969) that a central uplift can be formed by the detonation of a large charge on the ground surface, a process phenomenologically equivalent to the impact of a bolide.

Outside the Bluff highly disturbed strata have been observed out to 11km from the Bluff centre. From this and other investigations before the present survey, the zone of disruption was assumed to be a bowl 22km in diameter and 6.5km deep.

The formations exposed at the surface have been faulted into blocks several hundreds of metres long and several tens of metres thick. Some of these blocks have been displaced for considerable distances and even overturned. It is likely that this block-faulting has occurred throughout the disrupted zone. Much of the area inside and around the Bluff is covered by breccia which has been formed from the original debris strewn over the crater floor. This breccia has been found to be up to at least 160m thick and overlies - and perhaps underlies in places - dipping blocks of the Pertnjara Group or Mereenie Sandstone.

Shatter cones have been found to be associated with many presumed astroblemes (Dietz <u>in</u> French & Short, 1968). Milton has measured and analysed the orientation of shatter cones at Gosses Bluff and has deduced, by imaginary restoration of beds to the horizontal and to their presumed original position at depth, that the energy was propagated from a precise focus at most 600m below the pre-event ground surface (Milton et al., 1971).

Various stages of shock metamorphism in quartz are observed at Gosses Bluff (Milton et al., 1971). These effects can be ranked in a sequence of increasing metamorphism, and the peak pressures associated with them can be determined experimentally (Hörz <u>in</u> French & Short, 1968). Planar features in quartz grains, common at Gosses Bluff, are shown to form at shock pressures above 100 kilobars - which could be produced only by a massive detonation.

The age of the Gosses Bluff event has been determined to lie within the range 130 ± 6 million years, that is early Cretaceous, by both potassium/argon and fission-track dating methods.

OTHER GEOPHYSICS

Magnetic

A regional airborne magnetic and radiometric survey of the Amadeus Basin was carried out by BMR in 1965 (Young & Shelley, 1966). They estimated the depth to magnetic basement in the north-central region near Gosses Bluff to be approximately 10500m.

Richards (1958) and Brunnschweiler, Leslie, & Richards (1959) found a small magnetic anomaly associated with Gosses Bluff superimposed on a strong westerly gradient. The size of the anomaly suggested that the structure did not have an igneous core. Detailed aeromagnetic coverage of Gosses Bluff was obtained in 1968 as part of the BMR/USGS joint project (Young, 1970). This showed very little magnetic effect centred on the Bluff, but negative anomalies of up to 70 gammas were found from the northwest to the south and on the east side of the Bluff and were interpreted as being due to near-surface bodies that might have been overturned. The follow-up ground magnetic survey in 1969 found that the anomaly to the south of the Bluff was extremely intense and was associated with shock- melted breccia (Sedmik, 1971).

Model studies of the magnetic anomalies indicated pole positions which were not inconsistent with an early Cretaceous age. Oriented cores of the shock-melted breccia were obtained for palaeomagnetic study and this strongly favoured the same age (Manwaring <u>in</u> Sedmik, 1971).

Gravity

BMR conducted gravity surveys using helicopters in the Amadeus Basin in 1961 (Langron, 1962) and in 1962 (Lonsdale & Flavelle, 1963). Geophysical Associates (1965, 1967) took gravity readings along all their seismic lines in the northern part of the basin. The data indicate an asymmetrical elliptical basin with a regional gravity low in the north-central portion, suggesting that sediments are more than 9000m thick.

Semi-detailed gravity work on Gosses Bluff before 1967 indicated a circular gravity low. Richards (1958) suggested that this might be indicative of a salt intrusion and that a small positive feature in the centre of the Bluff could possibly indicate the presence of a cap-rock formation.

The 1968/69 Gosses Bluff Detailed Gravity Survey (Barlow, 1971) indicated an approximately circular residual gravity low of about 3 milligals with no central high. The residual anomaly pattern shows asymmetry similar to that of the surface fault pattern in the central uplift. Model studies most readily account for the anomaly by near-surface effects only.

Seismic

Seismic traverses were surveyed by the BMR in 1961 (Moss, 1962) to determine the structure of the southern margin in the eastern part of the Amadeus Basin and also (Turpie & Moss, 1963) to investigate the structure of the basin in the Palm Valley/Hermannsburg area.

In 1962 BMR surveyed a regional traverse across the Missionary Plain from the MacDonnell Ranges in the north through Gosses Bluff to the Gardiner Range in the south (Moss, 1964). The results indicated a maximum thickness of at least 10000m of sedimentary rock under the Missionary Plain to the north of Gosses Bluff. The quality of seismic data in the vicinity of the Gosses Bluff structure was very poor, with little continuity of reflections. However, all the seismic evidence available supported the theory that Gosses Bluff was a diapiric structure of the salt dome type, although none would discount the astrobleme theory. The Bitter Springs Formation was considered as the probable source of the necessary mobile material.

The geophysical surveys carried out during 1965 and 1966 by Geophysical Associates (1965, 1967) in the Missionary Plain area provided extensive seismic coverage over the northern part of the Amadeus Basin. The quality of the seismic data generally was good in the undisturbed regions and the reflection character was found to be very consistent. The results indicated that Gosses Bluff lies on an arcuate ancestral uplift, the Gardiner-Tyler Anticline, which extends northeast from the Gardiner Fault, through the Tyler Anticline to and possibly under the MacDonnell Ranges. The network of traverses, shown in Plate 1, provided an excellent base for the present survey, permitting the extremities of the traverses to be tied together and also tied to Palm Valley No. 1 and Tyler No. 1 wells.

The seismic data shot by Geophysical Associates also exhibited very poor reflection quality near Gosses Bluff. The deeper reflections in general continued closer to the centre. A marked improvement in reflection quality was obtained on Traverse 2-G using 4-fold common-depth-point (CDP) multiple coverage. The reason for the deterioration in record quality of both the company and earlier BMR work near the Bluff was the presence of shot-generated noise, particularly random noise, probably caused by the increased disturbance of the formations. The amount of random noise present in these data was clearly demonstrated by use of BMR's LaserScan optical processing equipment. It was not considered necessary on either of these surveys to make any particular effort to attenuate this noise as the objective of both was regional exploration. For a more detailed study, random noise can be attenuated by an increase in the number of holes, the number of geophones, or the multiplicity of the coverage. Coherent noise can be attenuated by careful design of the hole pattern, geophone pattern, and multiple coverage spread geometry.

OBJECTIVES

The request for seismic work at Gosses Bluff was made with the objective more of defining its various structural features more clearly, so that the type of structure to be expected from the impact of a body from space might be known more precisely, than of determining the origin of the structure. However, there were a few features of the structure capable of investigation by the seismic method, which could yield evidence on its origin.

The main objectives of the survey were to use seismic reflection and/or refraction methods:

1. To demonstrate the continuity and undisturbed character of the deeper horizons below the structure to determine if there is a limit to the depth of penetration of the disruptive force.

2. To outline the shape of the region of disrupted strata.

3. To determine if an intrusive material exists in the core of the structure.

Further objectives related to the details of the structure were:

4. To determine if a peripheral syncline surrounds the disrupted region.

5. To determine if the strata are folded into an anticline at depth in the centre of the structure.

6. To determine the attitude of the strata within the disrupted region and the dip and throw of the larger faults.

7. To determine if folds have been induced in the strata outside the region of disruption.

8. To map the areas and thicknesses of breccia present in the disrupted region outside the present Bluff.

9. To determine the relationship of the Gosses Bluff structure to the other structural features in the area, in particular the anticline on which Gosses Bluff stands.

PROGRAMME

Details of the field programme as originally planned and its relationship to what was actually carried out are given by Brown (1971a). This section presents a summary of the programme as executed. The locations of the seismic reflection traverses shot are shown in Plate 1. Traverse GB/A was 24km long and was oriented approximately parallel to the subsurface Gardiner-Tyler Anticline; Traverse GB/B was 28km long and was oriented across the anticline.

The survey planned a considerable increase in effort compared to previous seismic work in the vicinity of Gosses Bluff and also planned to record reflections from under the inaccessible Bluff walls by offset shooting. Large numbers of shot-holes and geophones were used to attenuate random noise, and these were laid in carefully designed patterns in order to attenuate coherent noise according to the principles elaborated by Smith (1956) and Fail (1962). Multiple coverage also was used where necessary, employing the methods of Mayne (1962, 1967).

The survey started in the southwest with experimentation to establish shooting and recording parameters. Recording on Traverse GB/A initially involved single coverage, but, as the Bluff was approached, the normally excellent reflection quality of the Amadeus Basin deteriorated significantly and multiple coverage was used within 7km of the Bluff centre. Continuous multiple coverage was obtained under the Bluff walls. Traverse GB/B, intersecting GB/A at Gosses Bluff No. 1 well inside the Bluff, was recorded in a similar manner.

Predominantly 3-fold CDP multiple coverage was used in the immediate vicinity of Gosses Bluff on both traverses. It had been planned to shoot 6-fold CDP but, with the shot-hole and geophone patterns in use, this had to be reduced in order to maintain a reasonable rate of production. Later, in a maximum effort attempt to establish the shallowest continuous reflections under the Bluff, 24-fold CDP was used on both traverses inside the Bluff's central pound.

The ends of both traverses intersected traverses shot by Geophysical Associates, thus permitting the correlation of seismic reflections on Traverses GB/A and GB/B around the outside of the Bluff and their correlation with formations penetrated by wells elsewhere in the Amadeus Basin. In order to facilitate this correlation around Gosses Bluff, Traverse GB/2-C was shot to close the gap between Traverses 2-C and 2-D.

Three expanded spreads for detailed vertical velocity determination were shot in regions of good reflection quality on Traverses GB/AA, GB/AB, and GB/BA. Velocity information was necessary for conversion of seismic data from time to depth scales and for processing the data, especially the CDP work. Also a request had been made for velocity information for the deduction of approximate formation densities to aid in the interpretation of the BMR gravity results from Gosses Bluff.

Tests using a controlled directional reception (CDR) method (Riabinkin et al., 1962) were made in an attempt to determine the attitude of the shallower strata near the centre of the structure.

Near-surface seismic velocities were determined from refraction breaks on reflection records in an attempt to delineate regions of brecciation. Some shallow refraction shots were recorded on Traverse 81/82, which was very close to a line along which Glikson (1969) mapped outcrops of bedrock and breccia in some detail. The shallow refraction programme was designed to determine the difference in seismic velocity between bedrock and different kinds of breccia and to provide a model on which could be based a relationship between seismic velocity and density in the Gosses Bluff area.

When a velocity survey (UGC, 1969) was being conducted in Tyler No. 1 well, 13.5km northeast of the centre of Gosses Bluff, the shots were recorded by a geophone spread at the well. This facilitated correlation between existing seismic data and formations penetrated by the well.

No refraction programme was undertaken other than the shallow refraction work on Traverse 81/82. A feasibility study indicated that velocities higher than the sub-weathering velocity were not recorded at offsets up to 4.2km. Thus, in order to penetrate to deeper refractors under the Bluff, a large-scale refraction study using offsets of many kilometres would have been required. Such a study would have been very time-consuming and it was considered that the refraction data from such a geologically complex area as Gosses Bluff might have been uninterpretable.

DATA RECORDING, PROCESSING, AND ANALYSIS

Recording Techniques

General. All data were recorded in analogue form on FM magnetic tape and on the principal traverses programmed gain was used exclusively. In this way instrumental distortion of the seismic signal was much less than if automatic gain control (AGC) had been used, and recovery of true amplitude was possible in later analysis or processing. Throughout the survey stringent quality control of the seismic records was exercised. Tests of the recording equipment were conducted regularly.

Field Experimentation. As part of the initial experimentation, a noise test was shot at SP 978, Traverse GB/A. The unfiltered record section, indication of the main noise and signal events, and a frequency-wavenumber diagram are shown in Plate 2. Filtered record sections are shown in Plate 3. The instrumental filters selected for recording and used throughout the survey were a low-cut filter of 16 Hz, 12 dB/octave, which was the lowest available, and a high-cut filter of 135 Hz. This gave a passband of over three octaves.

A group of eight geophones extended parallel to the traverse, with a spacing between geophones of 6m, was selected for recording on Traverse GB/A. The cut-off wavenumber of this group for in-line noise was 10 cycles/1000m. Events (5) and (7), which did interfere with major signal events, lay partly below the wavenumber cut-off but were attenuated by the low-cut filter.

The traverse noise test (Plate 2) demonstrated that there was no particular transverse noise problem. However, random noise was a known problem in the Gosses Bluff area, so a large number of geophones was known to be required. Four parallel rows of eight geophones each were used, giving a pattern of 32 geophones per trace. This provided a balance between random noise cancellation and productivity and was used with satisfactory results on the first part of Traverse GB/A.

Later, however, a low frequency, low velocity noise event (similar to event (5) on Plate 2) was evident on reflection records and was causing undesirable interference with signal. A test was conducted on Traverse GB/A between SPs 1005 and 1011 using a geophone group of twice the previous length in the direction of the traverse. The 32 geophones were arranged in two rows, each containing 16 geophones, 6m apart. This group had a cut-off wavenumber for in-line noise of 5 cycles/1000m and was found to attenuate the previously troublesome noise satisfactorily. In order not to increase ground mixing, the geophone station interval was increased from 33.5 to 67.1m. This arrangement was used for the greater part of Traverse GB/B and an increased rate of progress was achieved because of the larger geophone station interval.

The number of holes drilled for each shot was determined largely by rate of drilling and rate of recording, while maintaining the number as large as possible for noise cancellation. The most common shot-hole pattern used was three holes in line with the traverse and drilled to a depth of 26m.

Production Reflection Recording. The portions of Traverse GB/A and GB/B inaccessible to seismic operations are indicated on an aerial photograph of Gosses Bluff on Plate 8. The geophone spread geometry and the corresponding subsurface coverage obtained are shown in Plates 9 and 10 for Traverse GB/A and GB/B respectively. The spreads and coverage correspond precisely to, and are on the same scale as, the record sections presented in Plates 11 and 12. The latter plates also include details of the geophone patterns, shot patterns, and other significant parameters used in various parts of the traverses.

Single coverage was used on the ends of both main traverses beyond about 7km from the Bluff centre, where the reflection quality was fairly good. In all cases this involved split spreads with twelve geophone groups on either side of the shot-point and a double gap in the centre. Thus reciprocal traces were obtained between adjacent records.

Within about 7km of the Bluff centre 3-fold CDP multiple coverage was used. Except very close to the Bluff walls this involved a regular roll-along technique shooting every fourth geophone station into an off-end spread. The multiplicity was increased to 6-fold over a small portion of Traverse GB/A on the southwest side of the Bluff, where the reflection quality was found to be particularly poor. At the northeast end of the 3-fold coverage on Traverse GB/A the regular progression of spreads was disturbed where the traverse crossed a succession of creeks. In order to record continuous 3-fold coverage under the Bluff walls, a shot outside the Bluff was recorded by a geophone spread inside the Bluff or vice versa. This necessarily involved some very long offsets.

Initially 3-fold CDP was recorded inside the Bluff as part of the progressive shooting of the major traverses. Later, however, a maximum effort attempt was made to determine the shallowest continuous reflecting horizon beneath the Bluff by shooting 24-fold CDP inside the Bluff's central pound on both traverses. The intention was to record 12-fold CDP but it was necessary to employ the method of 24-fold CDP in order to obtain 12-fold coverage over a reasonable portion of the traverses. Plates 9 to 12 include the coverage and resultant data for the central portion on each traverse for which the multiplicity was 12 or greater. On either side of these portions is the previous 3-fold coverage.

Some pairs of traces included in the sets of CDP traces for certain depth points under the Bluff walls and the central pound were not strictly independent, that is they had traversed the same subsurface wave path. This arose when the inaccessibility of the Bluff walls made it necessary for more than one shot to be fired from the same shot-point. The stacking of such traces is of value in the cancellation of random noise but not of coherent noise. These non-independent traces do not appear distinct on Plates 9 and 10 and thus the multiplicity indicated is in some places less than that used in the stack.

After controlled directional reception (CDR) trials at Owen Springs, 130km east of Gosses Bluff (Brown, 1971b), it was used over a portion of Traverse GB/B outside the Bluff wall on the northwest side (Plate 12). In recording, the essence of the method is to use a long line of shot-holes perpendicular to the traverse and to extend geophone groups only perpendicular to the traverse. In this way the shot energy is concentrated into the plane of the traverse with no spatial filtering in this plane. Events from any direction in the plane of the traverse are thus recorded. Recommended CDR processing involves the summing of groups of adjacent traces with different time delays between them in order to enhance in turn events of different dips. This method of processing was not found to be particularly helpful (Brown, 1971b) but the method of shooting yielded better reflection quality in this region of fairly steep dip than did the 3-fold CDP. This was probably because the long in-line geophone group being used for recording the 3-fold CDP to some extent attenuated the dipping reflections, because of the large number of holes used for the CDR shooting and because the static corrections used in processing the CDP were not good.

Expanded Spreads. Three expanded spreads for determination of detailed vertical velocity information were shot on Traverses GB/AA, GB/AB, and GB/BA. All were recorded in the manner proposed by Musgrave (1962) and are presented in section form in Plates 4, 5, and 6. Traverses GB/AA and GB/BA were surveyed at right-angles to Traverses GB/A and GB/B respectively. This was done so that they would be approximately along the strike of any structural features associated with Gosses Bluff and also so that the shots and geophones would be in positions with more similar surface conditions. Traverses GB/AB was not perpendicular to GB/A because of local conditions of topography and scrub. The expanded spreads on Traverse GB/AB and GB/BA were recorded with the trace order on alternate records reversed; for that on Traverse GB/AA the trace order on alternate records was reversed during playback.

Processing Techniques

Analogue Processing. Every effort was made by means of analogue and digital processing techniques to extract the maximum amount of information out of the data recorded. Initially analogue processing of all magnetic tapes was undertaken using the BMR playback centre in Canberra.

Correction of records for normal moveout presented no major problem at Gosses Bluff. Seismic velocities in the rocks were high and there were no very shallow events of particular importance. Thus normal moveout was always small. It follows from this that the velocity function selected for correction of records prior to stacking was not critical, but, on the other hand, the determination of vertical velocities from normal moveout was necessarily difficult.

Elevation and weathering corrections for single coverage records were calculated on an individual trace basis from an analysis of first arrival times. For the multiple coverage shooting, uphole times were available at more closely spaced intervals along the traverses and the uphole correction method was considered adequate. These correction methods are discussed by Vale (1960). By examination of the initially corrected record sections the static corrections calculated as above were seen to be poor. In the case of the 3-fold multiple coverage data some reflections were being attenuated during stacking because of the poor alignment of reflections on the component traces input to the stack. Empirical adjustments to the static corrections were made after examining transparent overlays of single coverage sections. In this way improved alignment of reflections was achieved in most parts of the traverse; however, in some it proved impossible to devise static corrections which were applicable over all record times. In these cases residual static corrections were not applied.

For the 12- to 24-fold CDP inside Gosses Bluff difficulty was also experienced in determining empirical residual static corrections. These were therefore not applied, but a significant improvement in reflection quality of the 12-fold CDP data compared to the single coverage data inside Gosses Bluff was nevertheless achieved (Plate 15). Comparison of the success of the 3-fold and 12-fold CDP shooting in this area demonstrates that, where irregular surface conditions are liable to generate a static correction problem, a multiplicity higher than 3-fold is highly desirable.

The passband filter 20 to 60 Hz was found to yield the highest signal-to-noise ratio for the analogue processed data and has been used in the display of that part of the data in Plates 11 and 12 processed by analogue means only. The effect of this filter on the noise test records is shown in Plate 3.

Digital Processing. After initial analogue processing, some of the data in problem areas, which were principally close to and under Gosses Bluff itself, were subjected to digital processing in an attempt to improve reflection quality further. Digital processing was carried out under contract by Geophysical Service International (GSI) in Sydney. The sampling interval on transcription was two milliseconds and the anti-alias filter was 168 Hz. The principles of digital processing are described by United Geophysical Corporation (1966) and Silverman (1967) and are discussed in relation to data from the Roma Shelf Seismic Survey, 1967-68, by Brown & Willcox (1971).

The first batch of data to be processed digitally was the 12- to 24-fold CDP from inside Gosses Bluff on both traverses. This formed part of the attempt to establish with maximum possible degree of certainty the shallowest continuous reflecting horizon under the Bluff. The significant aspect of the processing of these data was deconvolution. Time-varying deconvolution (Clarke, 1968) with a 30-point operator was used and was found to be very successful in sharpening up the reflections by reducing the length of the wave-train associated with them (Plate 15).

Because of the success of this deconvolution and because of the difficulty by analogue methods of applying accurate moveout correction to traces recorded with very long offsets, the 3-fold data from all the long offset shooting under the Bluff walls were also digitally processed. So also were the CDR data from the northwest side of the Bluff on Traverse GB/B. Deconvolution was again helpful in sharpening up reflections.

The final output from the digital processing was transcribed onto analogue magnetic tapes so that these could be displayed by BMR in continuous sections along Traverses GB/A and GB/B, including analogue and digitally processed data (Plates 11 and 12). The passband filter used in the display of the digitally processed portions was 16 to 47Hz. This gave a presentation comparable with that of the analogue processed portions displayed using the filter 20 to 60 Hz. Both these passbands are 1.6 octaves wide.

Optical Processing. The LaserScan optical processing equipment (Dobrin, Ingalls, & Long, 1965) was used to examine the noise characteristics and frequency content of the sections shown in Plates 11 and 12. Two-dimensional Fourier transform patterns are shown in Plate 16 for portion of Traverse GB/A immediately northeast of the Bluff wall and the adjacent and radially equivalent portion of Traverse L, 1962 (Moss, 1964). The Traverse GB/A transform pattern shows a bright spot on the frequency axis which is probably signal and a reduced diffuse area around it compared to the earlier data, demonstrating that random noise has been reduced and signal-to-noise ratio increased.

Plate 16 also shows a one-dimensional transform pattern of a part of Traverse GB/B, some of which had been processed digitally and some not. The spectrum whitening effect of the deconvolution indicated by the even intensity in the pattern for the digitally processed portion shows that all frequency components have been brought to a uniform level within the frequency band passed by the playback filter.

Velocity Analysis

Expanded Spreads. In the absence of well data, determination of vertical velocities necessarily depends on the measurement of normal move-out. The three expanded spread sections (Plates 4, 5, and 6) were analysed for velocity determination by the method of t^2-x^2 proposed by Musgrave (1962). The RMS velocities deduced in the first instance by manual calculation indicated higher velocities to the north of Gosses Bluff than to the south, and, when interval velocities were calculated from these RMS velocities, many improbable values were obtained.

A computer program VELSPRED (Pettifer, 1971) was then used to compute RMS and interval velocities from expanded spread data. It was hoped that this more objective approach, calculating as it did standard deviations of all computed quantities, would yield more reliable velocity information. Plate 7 shows RMS velocity as a function of reflection time computed for those reflections indicated on the expanded spread sections.

The interval velocities computed using VELSPRED were still somewhat improbable and have been of little value for the determination of formation densities. The reason for this situation is assumed to stem from interference on the expanded spread sections, which is clearly visible in some places. It is considered that the RMS velocity results are meaningful whereas the interval velocities, which are mostly calculated over small time intervals, are not.

The velocity function deduced by t-Δt analysis of normal moveout on the single coverage reflection records recorded with 805m split spreads at the southest end of Traverse GB/B is also shown in Plate 7. Other similar analyses conducted on records from other parts of the traverses yielded unreliable results either because the spreads were shot off-end or because split spreads were too short for the moveout to be easily measurable.

Moveout Scans. In an effort to obtain vertical velocity information close to the Bluff in the region where there was known to be considerable disruption of the rocks, several Moveout Scans were conducted as part of the digital processing carried out by GSI. The input to Moveout Scan is usually 24 traces which have not been corrected for normal moveout and which correspond to one or a small number of adjacent common depth points depending on multiplicity. The method is most successful with high multiplicity data. The process systematically applies a range of moveout corrections, finds the moveout which yields the maximum amplitude after stack for each reflection, and computes the RMS velocity from that moveout.

The results of velocity determinations by Moveout Scans and expanded spreads along Traverse GB/A are presented as profiles of RMS velocity to record times of 1.5, 2.0, 2.5, and 3.0 seconds in Plate 18.

Initially several Moveout Scans were conducted on the high multiplicity data from inside Gosses Bluff. There was a considerable scatter of resultant velocity-time points, but it was possible to fit a plausible straight line to the data. In order to gain corroborative evidence for the very low velocities indicated, further Moveout Scans were then conducted on the 3-fold data from Traverse GB/A just outside the Bluff walls and also towards the outer limit of the 3-fold coverage. The input data to these Scans was not ideal, as each required the use of eight adjacent depth points. However, it was again possible to deduce plausible velocity functions from the Moveout Scan outputs.

Moveout Scans were used on the expanded spread data of Traverses GB/AA and GB/AB as a check of the method of t^2-x^2 analysis vis-a-vis Moveout Scan. For Traverse GB/AA the results were very similar. For Traverse GB/AB the velocities deduced by Moveout Scan were significantly lower than those deduced by t^2-x^2 analysis. Moveout Scan was repeated on these data using different input traces, and still a lower, although not quite so much lower, velocity function was obtained. The velocity points plotted for Traverse GB/AB are means of those deduced by Moveout Scan and t^2-x^2 analysis. This difference in velocities calculated for Traverse GB/AB must cast some doubt on the high velocities shown for this traverse on Plate 7.

The velocity profiles along Traverse GB/A (Plate 18) demonstrate a significant reduction in seismic velocity centred on Gosses Bluff. At first sight this is easy to explain as being due to the large-scale disruption of rocks in the structure. However, if those velocities are used in time-depth conversion for certain seismic reflections (those interpreted on Plates 13 and 14), a major hump is generated on all horizons on the resultant depth section. This also is shown in Plate 18. As the deepest of these horizons is believed to originate close to basement, it follows that the humps on the two major traverses imply a very large dome in metamorphic basement. This seems improbable, particularly as its position directly under the Bluff suggests that such a dome must be associated with the structure of the Bluff. Further, such a basement dome should be detectable magnetically and none has been identified (Young, 1970).

In the light of this situation a critical assessment was made of the reliability of velocity determinations in a disturbed zone such as at Gosses Bluff. Taner, Cook, & Neidell (1970) consider the limitations of the seismic method, including velocity determination, in abnormal situations and conclude that 'in areas of complex geology some unexpected RMS velocity curves are possible'. They stress that velocity determinations depend critically on the assumption of local linearity of subsurface interfaces. They used computer model studies to show that a velocity at the base of a simple syncline could be measured to be 30% below its true value. This is the magnitude of the reduction in velocity at Gosses Bluff indicated by the Moveout Scans.

Interpretation of the low RMS velocities from the Moveout Scans in terms of plausible interval velocities was extremely difficult. Finally these low velocities were discarded on the premise that the basic assumptions used in their calculation were invalid.

The deepest seismic reflections on Traverse GB/A, which runs along the Gardiner-Tyler anticline, show only minor relief in time. It seems unlikely that any large velocity feature such as that discussed above would be cancelled almost completely by a structural feature. This supports the conclusion that there is no significant velocity low associated with the structure. The small size of the gravity anomaly associated with Gosses Bluff and its interpretation as being most probably caused by predominantly shallow effects (Barlow, 1971) is also consistent with this.

Selection of Velocity Function. In the light of all the difficulties and inaccuracies discussed above of detailed velocity determinations in the Gosses Bluff area, it was decided that a velocity function constant in space and simple in time was the most satisfactory that could be deduced. Such a function would have the advantage of being easy to apply in further processing, particularly in migration. From the data of RMS velocity versus reflection time (Plate 7) the velocity function

$$V_{RMS}\ (m/s) = 3350 + 590t$$

was selected and assumed to be applicable to all the seismic data recorded during the survey. Because of the gradient of this function, the assumed constancy of velocity and thus gross density horizontally through the Bluff at any level requires that fracturing has caused the older, denser rocks raised as a result of the Gosses Bluff event to assume a decreased density very similar to that of the younger rocks which were previously at the same depth.

Although for the reasons mentioned above a velocity function uniform over the area of the survey was selected, there remain two possible measurable velocity perturbations. Firstly, a small time trough on the deeper reflections occurring at the centre of the Bluff on both Traverses GB/A and GB/B may indicate that a very slight reduction in vertical velocity is associated with the disruption. In order that basement does not show this trough after conversion to depth, the velocity function at the very centre of the Bluff requires to be as shown by the broken line on Plate 7. Secondly, the velocities measured on Traverse GB/AB by t^2-x^2 analysis or Moveout Scan are higher than the velocities determined elsewhere in the area. Thus there appears to be a real effect of higher velocities to the north of Gosses Bluff close to the MacDonnell Ranges.

Other Analysis

Shallow Velocity. First arrival times from all records were plotted against shot-to-geophone distance along the lengths of Traverses GB/A and GB/B. From these plots sub-weathering refraction velocities were calculated and are presented as a smoothed profile along each of the traverses in Plate 19. The velocities calculated from the 3-fold coverage records are less reliable than those calculated from the single coverage split spread data. Areas of disruption and of breccia are very approximately indicated on the profiles by the lower velocities.

Attenuation of Energy. On the premise that attenuation of seismic energy would be greater in the disrupted zone, an analysis of attenuation was conducted along each traverse in an attempt to derive some measure of the shape of the zone of disruption. Programmed gain parameters were used to recover actual signal amplitudes for one reflection continuous under the Bluff along Traverses GB/A and GB/B. These amplitudes were then normalized for charge size and reflection time and plotted as profiles along each traverse. A pattern of amplitude maxima and minima emerged, but so far this has eluded interpretation. Factors which were not taken into account in this analysis and which are probably important in the study of seismic energy are the ground coupling characteristics of the shot and waveguide effects along sub-vertical strata.

RESULTS

Uninterpreted seismic record sections for Traverses GB/A and GB/B are shown in Plates 11 and 12. Traces were recorded between SPs 998 and 1001 with twice the spacing used elsewhere on Traverse GB/A, but each trace has been played out twice contiguously in order to preserve uniformity of trace spacing on the section. The late first arrivals of energy under the Bluff walls on both traverses indicate the regions where long offset shooting was used.

At the right hand end of both sections the reflections lack resolution and many conflicting events may be seen. The poor reflection quality is assumed to be due to the complex geological structure close to the foothills of the MacDonnell Ranges and to surface conditions close to creeks. Higher effort in the field here would probably have yielded improved results.

The network of seismic traverses in the region of Gosses Bluff provided a means of correlating reflections between the ends of Traverses GB/A and GB/B. Traverse GB/2-C was shot to close a gap in the inner loop of traverses around the Bluff between Traverses 2-C and 2-D. The Traverse GB/2-C record section (Plate 22) has been corrected to the elevation datum used by Geophysical Associates for Traverses 2-C and 2-D and differs from that used for the BMR traverses in the present and previous surveys.

The principal reflecting horizons interpreted by Geophysical Associates (1965, 1967) over the Missionary Plain have been interpreted on Traverses GB/A and GB/B (Plates 13 and 14). These horizons have been correlated with the geological formations penetrated in Palm Valley No. 1, Tyler No. 1, and other wells as follows:

A - near base of Mereenie Sandstone

B - within Horn Valley Siltstone

C - near middle of Pacoota Sandstone

D - near base of Hugh River Shale

E - near top of Bitter Springs Formation

Several other events have been interpreted on Traverses GB/A and GB/B. Reflections P and Q have been correlated around the Bluff and are tentatively identified as follows:

P - near top of Pertatataka Formation

Q - near top of Heavitree Quartzite

Those reflections interpreted in the early part of the sections, namely those above reflection A, have been picked independently of each other. It was not possible to correlate them around the Bluff along the network of earlier traverses.

In the Amadeus Basin generally no reflecting horizons have been interpreted deeper than that associated with the Bitter Springs Formation (Horizon E). The events below this at the southeast end of Traverse GB/B are considered to be multiples. However, closer to the Bluff, particularly between SPs 1986 and 1991, a distinct event is evident. This has been picked as Horizon Q and is interpreted as originating close to basement, probably near the top of the Heavitree Quartzite. This event can also be distinguished close to Gosses Bluff on most of the earlier seismic traverses.

The selection of a simple linear velocity function applicable to all the seismic data in the Gosses Bluff area made it possible to use the computer program DIPLOTA (Harrison, 1971) to migrate reflections to their true position in depth. The reflections interpreted on Plates 13 and 14 are displayed as migrated depth sections in Plate 17.

Contours of reflection time to Horizon E, the approximate top of the Bitter Springs Formation, have been drawn to better illustrate the structure at depth under Gosses Bluff (Plate 23). The data from all earlier seismic traverses were incorporated and the plate is in effect an extension of a contour map presented by Geophysical Associates (1967) in towards the centre of the Bluff, but on a different datum.

The reflection time interval between Horizon E and Horizon Q is contoured in Plate 24. All seismic traverses have been used over the area within which Horizon Q can be distinguished on the record sections.

INTERPRETATION

Interpretation of the results presented in the last chapter enabled the structural features of Gosses Bluff to be defined more clearly and also provided some evidence relating to the origin of the structure. The achievement of each of the survey objectives as set out in chapter 4 is dicussed in turn below.

1. The deeper seismic horizons beneath Gosses Bluff, although somewhat variable in character, are continuous (Plates 13, 14, and 17), which demonstrates that there is a limit to the depth penetration of the disruptive force. This is not greater than 5500 metres below the present ground surface. The continuity of reflections P and E, considered to originate from near the top of the Pertatataka Formation and Bitter Springs Formation respectively, indicates the lack of significant disturbance immediately above the Bitter Springs level.

2. The shape of the zone of disrupted strata and the gross subsurface structure of Gosses Bluff were deduced from the seismic results with the aid of surface geology and gravity information.

There is a distinct region of no reflections in the centre of both traverses (Plate 17), which indicates the approximate extent of the deeper part of the zone of disruption. The shape appears to be hemispherical and, by inscription with the positions of good quality reflections recorded, the hemisphere was deduced to be of radius 4.3km with its centre in the ground surface. The disruption could, however, be more extended in depth, having more the form of a prolate spheroid.

The surface geology along Traverses GB/A and GB/B was supplied by D.J. Milton (pers. comm.) and is shown in simplified form in Plate 19. The approximate angles of dip measured at the surface are indicated and so is Gosses Bluff No. 1 well.

The subsurface geology was deduced by fitting the probable stratigraphy at Gosses Bluff (Table 1) into the sequence of migrated seismic horizons (Plate 17) identified by well correlation.

A cross-section along Traverse GB/B showing the probable gross structure of Gosses Bluff (Plate 20) was then drawn by schematically connecting the formation boundaries interpolated at depth with the boundaries mapped at the surface. Within the zone of disruption formations are probably greatly faulted into blocks. These blocks have been estimated by Milton (pers. comm.) to be of the order of 300m x 300m x 150m. This is the mean size shown.

The shape of the shallower part of the disrupted zone has been approximately defined from the deduction by computer of theoretical models which fit the gravity data (Barlow, 1971) and also by inscription within unpicked shallow seismic reflections, which can be seen on the record sections. Further evidence for the limit of disruption at the surface of 11.5km is supplied by the geological mapping of Glikson (1969) and by the sub-weathering velocity profile (Plate 19).

Both parts of the disrupted zone discussed above are regions of fractured but coherent bedrock; in addition there are small regions of chaotic deformation mapped at the surface as pockets of breccia (Glikson, 1969).

The shape of the zone of disruption is similar to that proposed for the Ries Crater in Bavaria (Milton, pers. comm.). However, a simple bowl is proposed for most of the meteorite craters studied in Canada by Innes (1961, 1964), who deduces that the disruption associated with a crater extends to a depth approximately equal to one-third of the crater's diameter. If for Gosses Bluff the crater diameter was slightly less than the overall diameter of the structure, that is about 20km, then the depth limit of disruption suggested would be between 6 and 7km, or somewhat greater than even the maximum value of 5.5km deduced from the seismic results.

3. The continuity of the deeper horizons beneath Gosses Bluff demonstrates that there is no large intrusive core in the structure.

4. There is no direct evidence from the seismic record sections of a peripheral syncline associated with the formation of Gosses Bluff. However, a peripheral syncline about 8km from the Bluff centre may have resulted from later inward salt movement in the Bitter Springs Formation.

5. Within the zone of no reflections associated with the disrupted region it was not possible to deduce any structural information. Thus there is no indication that the strata were folded into an anticline at depth in the centre of the structure as a result of the Gosses Bluff event. However, there is evidence of later anticlinal doming at the Bitter Springs level.

6. Similarly, it was not possible to map the attitude of the strata within the disrupted zone and the dip and throw of the larger faults.

7. There is no evidence that folds have been induced in the strata outside the region of disruption.

8. The regions of lower sub-weathering refraction velocity may indicate areas of breccia and disruption along the two seismic traverses. However, they are a very approximate guide only. Accurate determination of breccia zones and their thicknesses would have required a separate shallow seismic refraction programme, such as that conducted along Traverse 81/82 (Appendix 1).

9. It was possible to determine the relationship of the Gosses Bluff structure to some other structural conditions in the area, in particular the Gardiner-Tyler Anticline. Plate 23 indicates that Gosses Bluff stands above a pronounced local anticlinal dome at the Bitter Springs level. The interval contoured in Plate 24 corresponds approximately to the time thickness of the Bitter Springs Formation and thus the contours indicate a marked local thickening of this formation elongated along the axis of the anticline and located symmetrically under Gosses Bluff. Formation thicknesses determined regionally from seismic results (Geophysical Associates, 1967) indicate that the Gardiner-Tyler Anticline, perhaps initiated by the formation of a salt pillow, is an ancient structure whose growth ended in early Palaeozoic time (Froelich & Krieg, 1969). The impact hypothesis demands that the location of Gosses Bluff on the axis of this anticline is a coincidence. Its location above such a pronounced local domal thickening of the salt could also be a coincidence. However, it seems most probable that further growth of the already existing salt pillow was initiated locally by the Gosses Bluff event.

Velocities measured to the north of Gosses Bluff have been shown to be higher than to the south. Tyler No. 1 well, which was drilled close to the MacDonnell Ranges to the northeast of the Bluff, penetrated formations with a much higher velocity than had been predicted from drilling and seismic work farther south (Huckaba & Magee, 1969). This is thought to be a consequence of secondary silicification that filled most of the pore space in the rocks at Tyler No. 1. An increase in silicification near the MacDonnell Ranges may also be the reason for the higher velocities measured north of Gosses Bluff.

ORIGIN OF GOSSES BLUFF

Glikson (1969) compares the principal hypotheses which have been proposed to explain the origin of Gosses Bluff. The astrobleme or impact hypothesis is currently favoured by most workers and all the reasoning in favour of this interpretation is given by Milton et al. (1971). It would be inappropriate here to repeat all this material, much of which involves detailed geological reasoning. However, the significant results which supply evidence on the origin of the Bluff have all been presented in previous chapters and are summarized in Table 2.

Assuming that Gosses Bluff was formed by impact of an extra-terrestrial body, the stages in its formation are shown diagrammatically by Milton et al. (1971). Briefly these involved the outward propagation from the burst of an approximately hemispherical shock front. This caused shatter coning in the undisplaced strata. The rarefaction wave following the shock wave caused displacement of the rocks inward and upwards towards the original focus. This movement produced the central uplift of the structure and also, as extensive fracturing of the rocks must have resulted, the approximately hemispherical zone of disruption. Surface waves travelling outward from the focus caused the shallower disc-shaped disrupted zone.

This concept differs significantly from that proposed by Dence (in French & Short, 1968) who believes central uplift to be caused by slumping of the crater walls. Roddy (in French & Short, 1968) has found the ratio of vertical distance of structural uplift to crater diameter to be 8% for several craters.

Table 2. Gosses Bluff Astrobleme - summary of evidence on origin

Evidence \ Origin hypothesis	Is evidence consistent with origin hypothesis?				
	Igneous plug	Salt diapir	Mud volcano	Crypto-volcano	Astrobleme
1. No magnetic anomaly centred on Bluff (page 6)	No	Yes	Yes	Yes	Yes
2. Central uplift formed by rapid upward and inward motion (page 5)	No	No	No?	Yes?	Yes
3. Shock wave radiated from precise focus near ground surface (page 5)	No	No	No	No	Yes
4. Limit to depth penetration of disruptive force above formation likely to cause diapirism (page 19)	No	No	No	Yes	Yes

This figure is 15% for Gosses Bluff, which may suggest immediate response to the rarefaction wave as the more likely mechanism of central uplift. Further, the outward propulsion of blocks from the central uplift at Gosses Bluff, as indicated by their present position, seems inconsistent with slumping.

Using the relationship between crater diameter and energy proposed by Innes (1961), the energy of the Gosses Bluff event can be shown to have been of the order of 10^{20} joules. This could have been the kinetic energy of a low density, high velocity comet or a high density, low velocity meteorite. Penetration of a bolide depends more on its density than its velocity. The shallow depth of burst indicated by shatter cone data suggests that the bolide was more probably a comet.

CONCLUSIONS

The seismic survey was successful in obtaining better quality data than had been recorded previously in the area of Gosses Bluff. The CDP multiple coverage shooting in particular was valuable, although in some places a higher multiplicity than that used would probably have given further improvement. The experience gained in the use of multiple coverage methods indicated that, in an area where non-uniform surface conditions make the determination of accurate static corrections difficult, 3-fold CDP is insufficient multiplicity of coverage for a really successful stack.

The major objectives of the survey were achieved. The principal conclusions on the structure and origin of Gosses Bluff which can be drawn from the seismic results are as follows:

1. Continuous seismic reflections were recorded under Gosses Bluff at times greater than 2.3 seconds, demonstrating the continuity of formations lying above the salt-bearing Bitter Springs Formation.

2. There is a limit to the depth penetration of the disruptive force which is not greater than 5500m below the present ground surface. However, the most probable shape of the zone of disruption is describable schematically as a hemispherical bowl of radius 4300m with its centre in the surface, superimposed on a shallow disc extending to a maximum depth of 800m and to a radius of 11.5km.

3. The relationship between seismic velocity and depth has remained approximately uniform over the Gosses Bluff area, despite the disruption of rocks at depth and their displacement horizontally and vertically.

4. The seismic evidence is entirely consistent with Gosses Bluff being an astrobleme.

5. All information indicates that a salt pillow exists in the Bitter Springs Formation under Gosses Bluff. It is most likely that it first formed as part of the Gardiner-Tyler Anticline, on which movement was complete in early Palaeozoic time, and that the impact initiated further growth locally.

A further conclusion deduced from geological and magnetic results must be added:

6. Gosses Bluff was formed by the impact of a comet during the Cretaceous period 130 million years ago.

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APPENDIX I

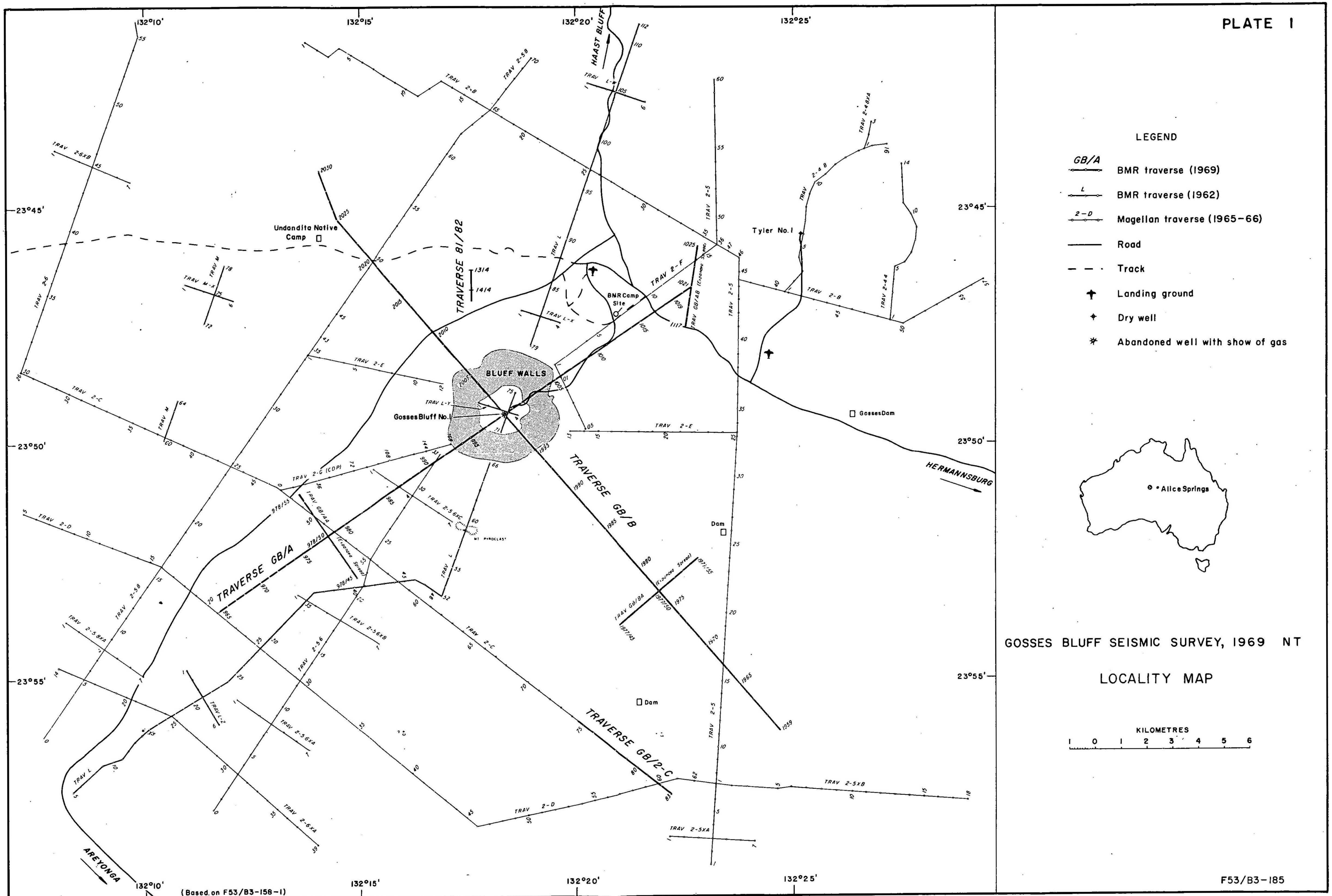
Shallow seismic refraction profile on Traverse 81/82

Traverse 81/82 was a gravity traverse (Barlow, 1971) oriented north-south and passing through gravity stations 1314 and 1414 (Plate 1) of the Gosses Bluff gravity grid. It was located close to a line along which Glikson (1969, figure 4) mapped outcrops of bedrock and breccia in some detail. The shallow refraction programme was designed to determine the difference in seismic velocity between bedrock and different kinds of breccia and to provide structural information which could be used in the verification of a relationship between seismic velocity and density in the Gosses Bluff area to aid gravity interpretation. The cross-section deduced is shown in Plate 21.

Single geophones were used with an interval of 16.8m. Three geophone spreads each 386m long were laid successively and each was used to record shots 16.8 and 402m off either end.

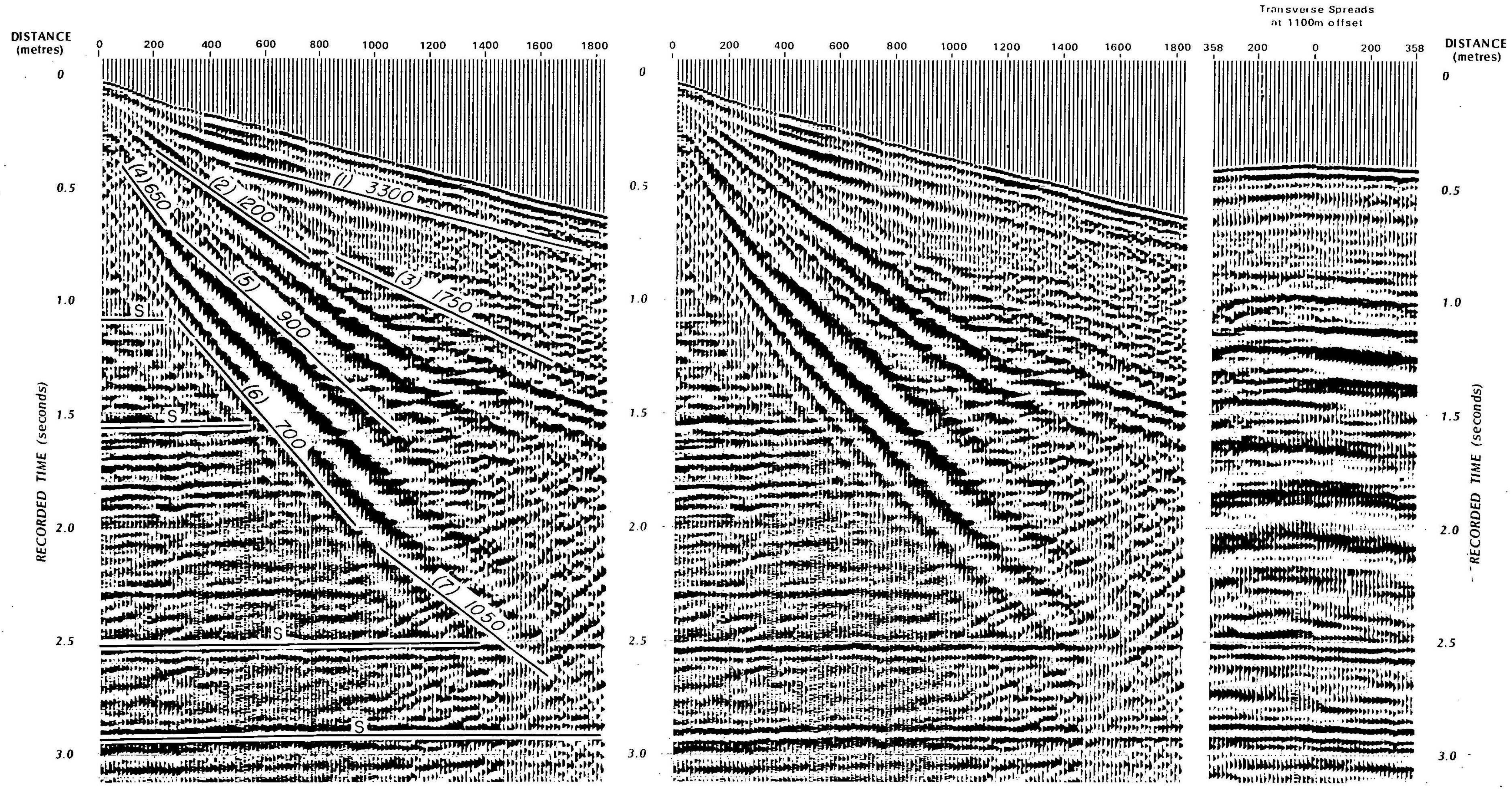
The time-distance data were analysed principally by the Reciprocal Method of Hawkins (1961) to determine the depth to and velocity in refracting layers. Surface geology, drill holes Hermannsburg Nos. 19 and 20 (Glikson, 1969), Hermannsburg Nos. 35, 36, and 37, and seismic shot-holes supplied some control. The position of the fault indicated was deduced from gravity results. Surface dips measured in the bedrock at the southern end of the traverse support the fault angle shown.

Different seismic refraction velocities have been determined for bedrock and two kinds of breccia known to be different. Using one of the established relationships between seismic velocity and density, the theoretical gravity profile derived from the cross-section has been shown to be in agreement with the observed residual Bouguer anomaly profile (Barlow, 1971). This has indicated the validity of this relationship in the Gosses Bluff area.



To Accompany Record No. 1971/141

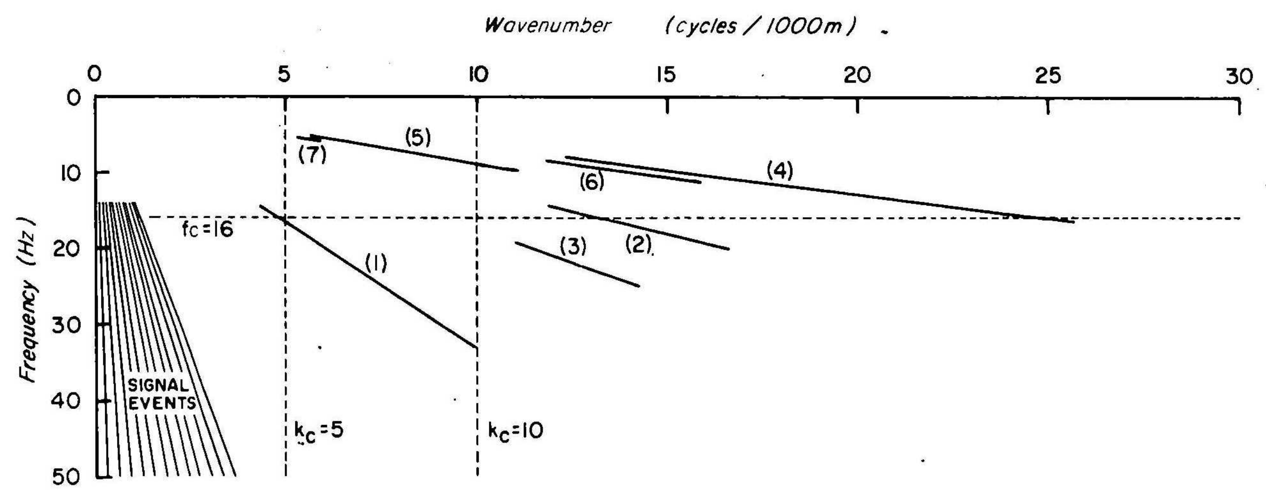
PLATE 2



(3) Identification of noise event

1750 Velocity of noise event in m/s

S Signal event



To Accompany Record No. 1971/141

RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder : PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : Out

Programmed Gain :

Function : A

Geophones : HS–J, 14Hz

Geophone Station Interval : 15.2m

Geophone Pattern :

8/trace bunched

Shot Hole Pattern :

Single
Depth 31 – 36m
Charge 27kg

PLAYBACK INFORMATION

Filters : Out

AGC : SS

Compositing : Nil

VELOCITY INFORMATION

Nil

HORIZONTAL SCALE

as indicated

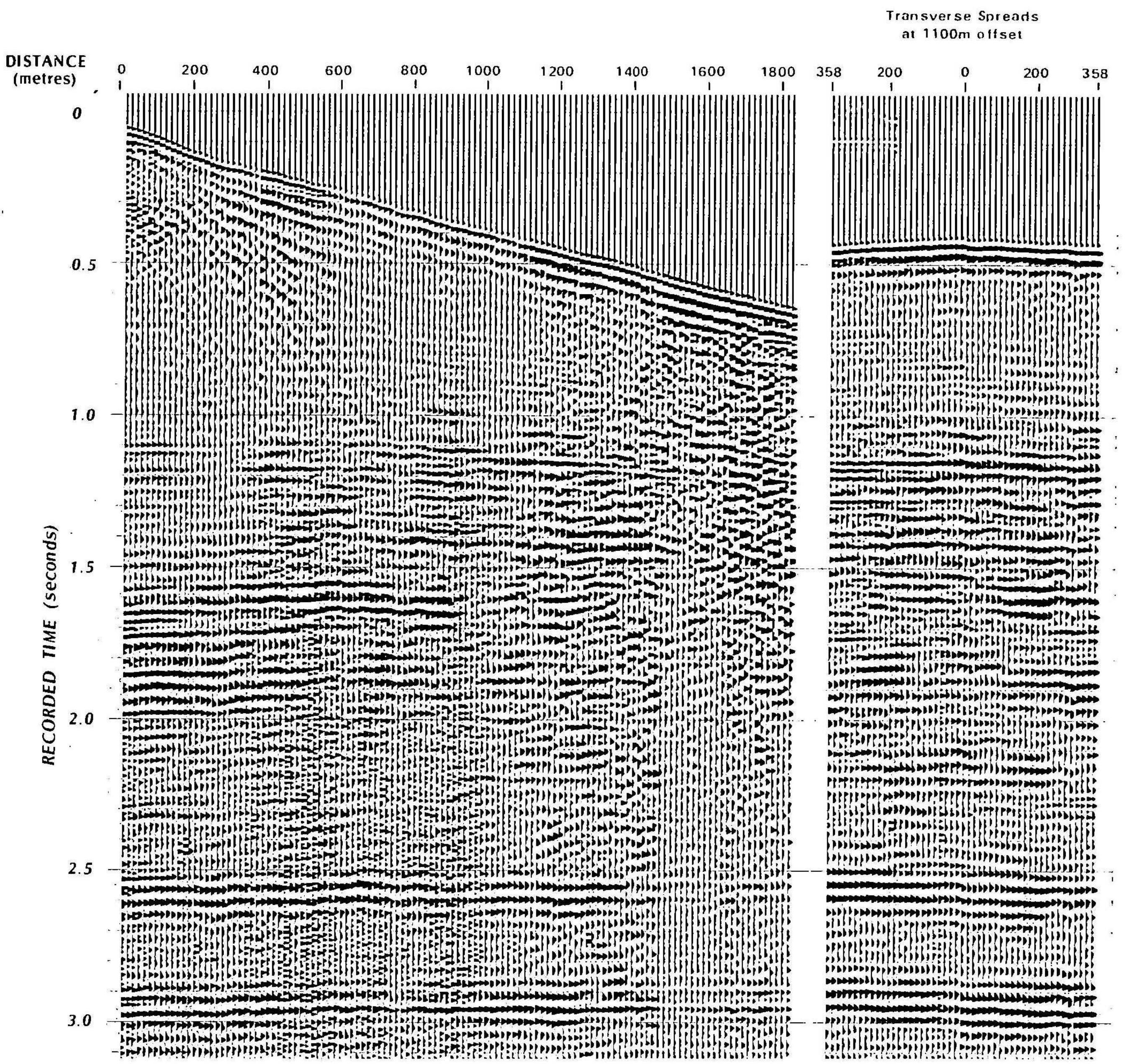
GOSSES BLUFF SEISMIC SURVEY, 1969

NOISE TEST

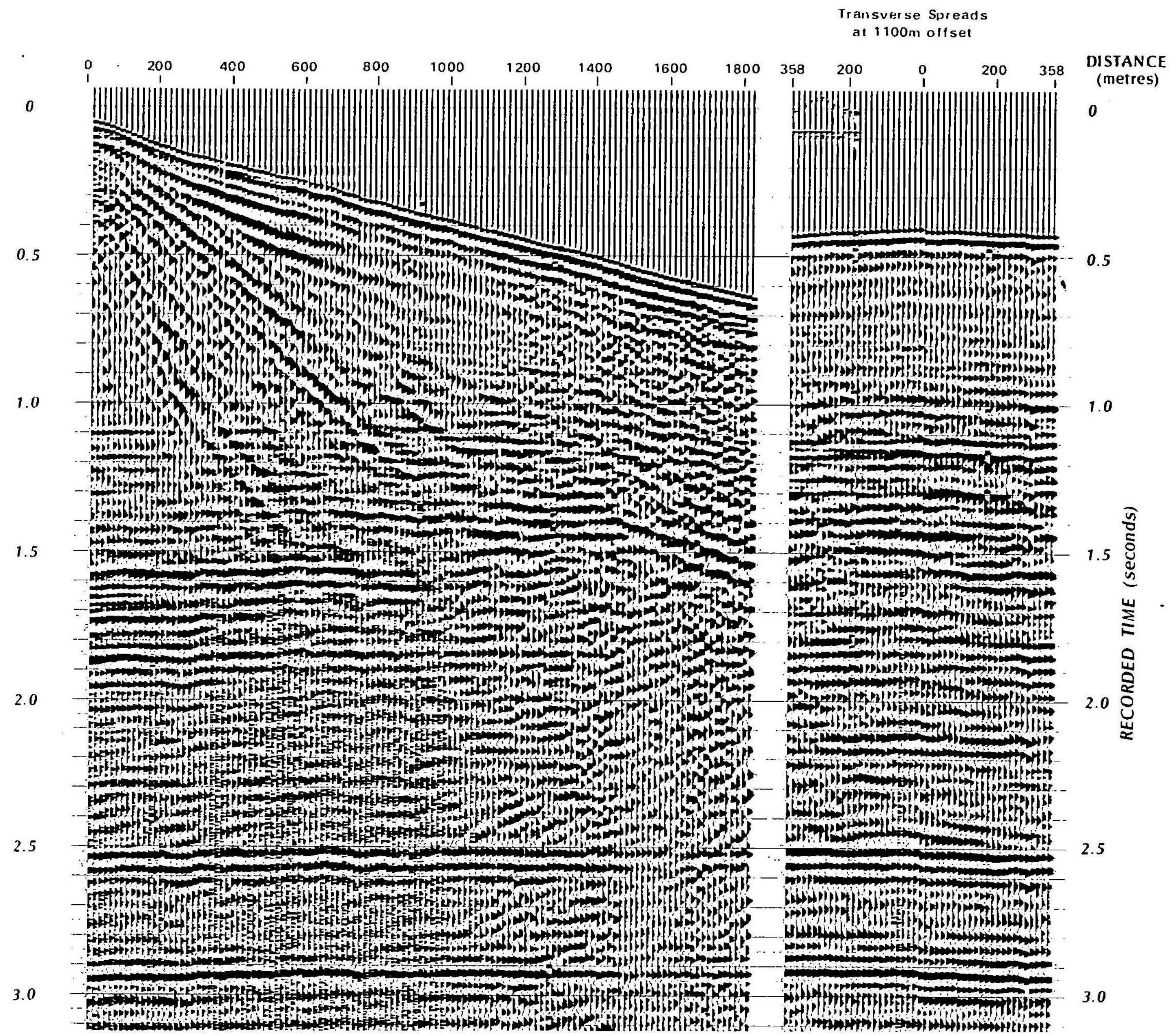
TRAVERSE GB/A SP978

F53/B3–171

PLATE 3



Playback Filters: LL20 – KK60
(playback filters used for
sections in Plates 11 and 12



Playback Filters: L16 – KK135
(normal recording filters used
on Traverses GB/A and GB/B)

To Accompany Record No. 1971/141

RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder : PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : Out

Programmed Gain :

Function : A

Geophones : HS–J, 14Hz

Geophone Station Interval : 15.2m

Geophone Pattern :

8/trace bunched

Shot Hole Pattern :

Single
Depth 31 – 36m
Charge 27kg

PLAYBACK INFORMATION

Filters : as indicated

AGC : SS

Compositing : Nil

VELOCITY INFORMATION

Nil

HORIZONTAL SCALE

as indicated

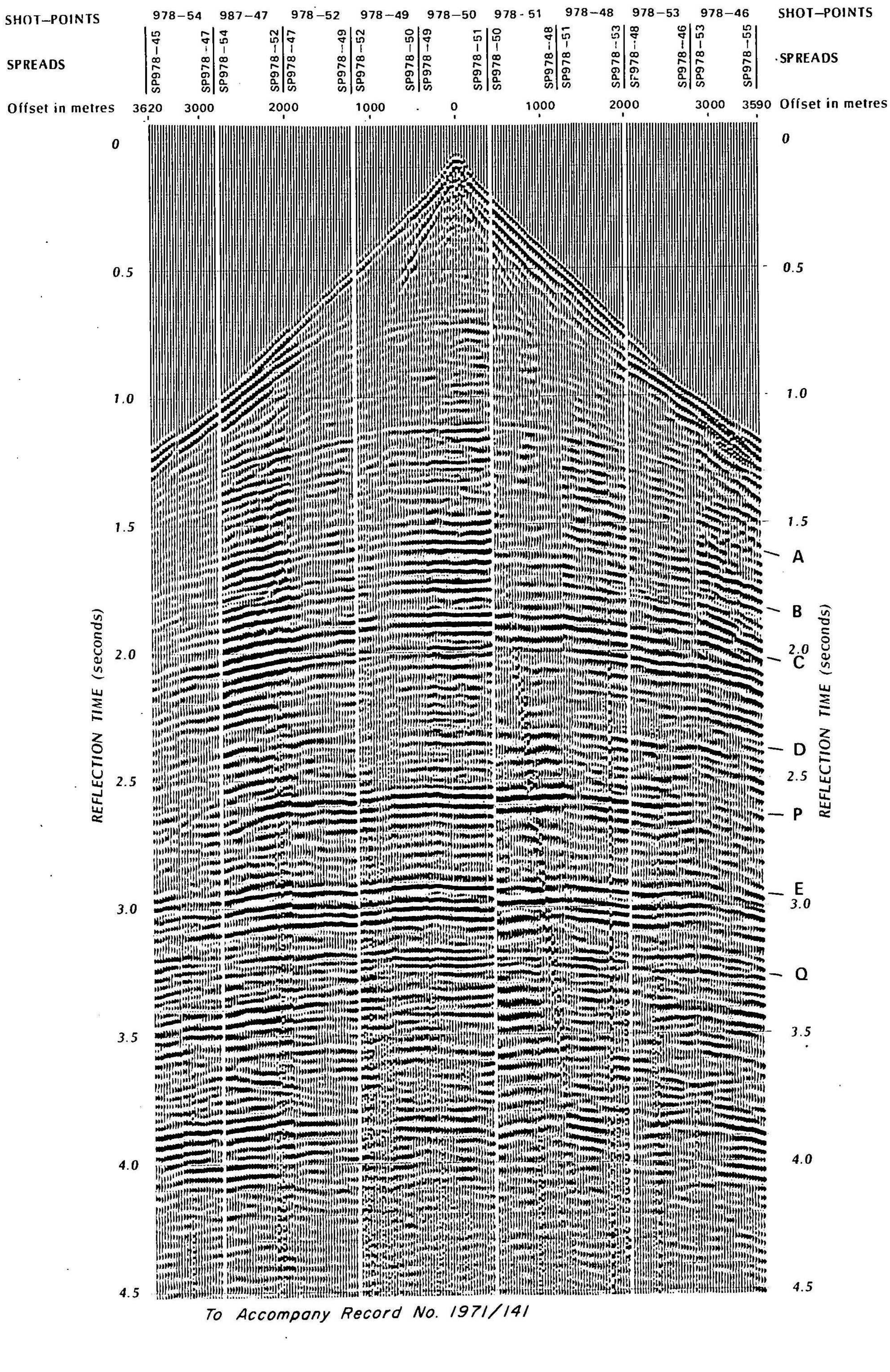
GOSSES BLUFF SEISMIC SURVEY, 1969

NOISE TEST

TRAVERSE GB/A SP978

F53/B3–170

PLATE 4



To Accompany Record No. 1971/141

RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder : PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : L16 – KK135

Programmed Gain :

Function : A

Geophones : HS–J, 14Hz

Geophone Station Interval : 33.5m

Geophone Pattern :

32/trace in 4 rows of 8 in line
Rows 9m apart, geophones 6m apart

Shot Hole Pattern :

3 holes, 15m apart in line
Depth 19 – 26m
Commonest charge 3 x 36kg

PLAYBACK INFORMATION

Filters : LL20 – KK60

AGC : SS

Compositing : Nil

VELOCITY INFORMATION

Nil

HORIZONTAL SCALE

as indicated

Note: Reflections identified are
those interpreted on Plates 13 and 14

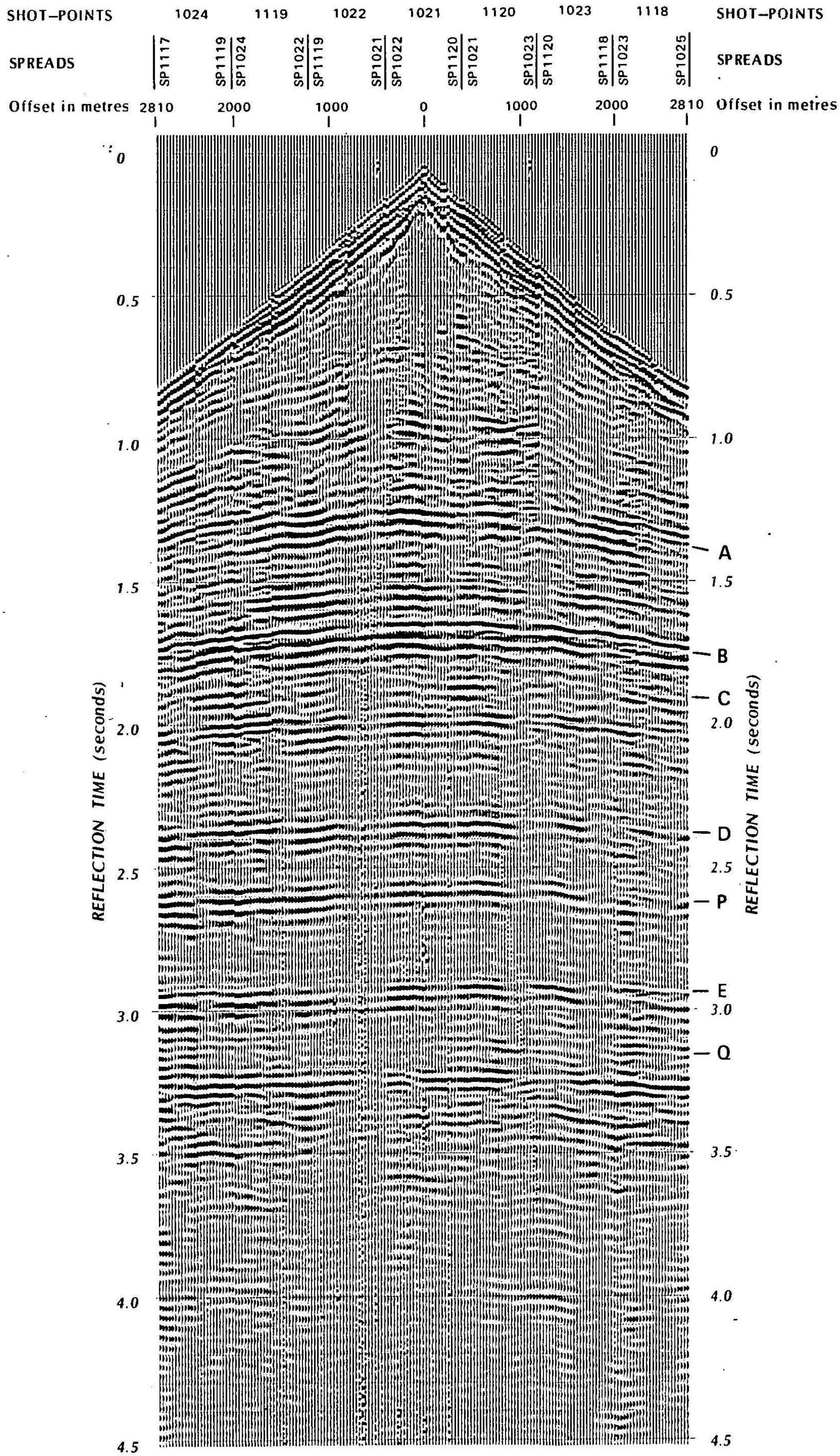
GOSSES BLUFF SEISMIC SURVEY, 1969

EXPANDED SPREAD GB/AA
centred on Traverse GB/A SP978

F53/B3–169A

PLATE 5

RECORD SECTION



To Accompany Record No. 1971/141

RECORDING INFORMATION

Magnetic Recorder : PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : L16 – KK135

AGC : S

Geophones : HS–J, 14Hz

Geophone Station Interval : 33.5m

Geophone Pattern :

16/trace in 2 rows of 8 in line
Rows 9m apart, geophones 6m apart

Shot Hole Pattern :

2 holes, 15m apart in line
Depth 20 – 26m
Commonest charge 2 x 45kg

PLAYBACK INFORMATION

Filters : LL20 – KK60

AGC : Off

Compositing : Nil

VELOCITY INFORMATION

Nil

HORIZONTAL SCALE

as indicated

Note: Reflections identified are those interpreted on Plates 13 and 14

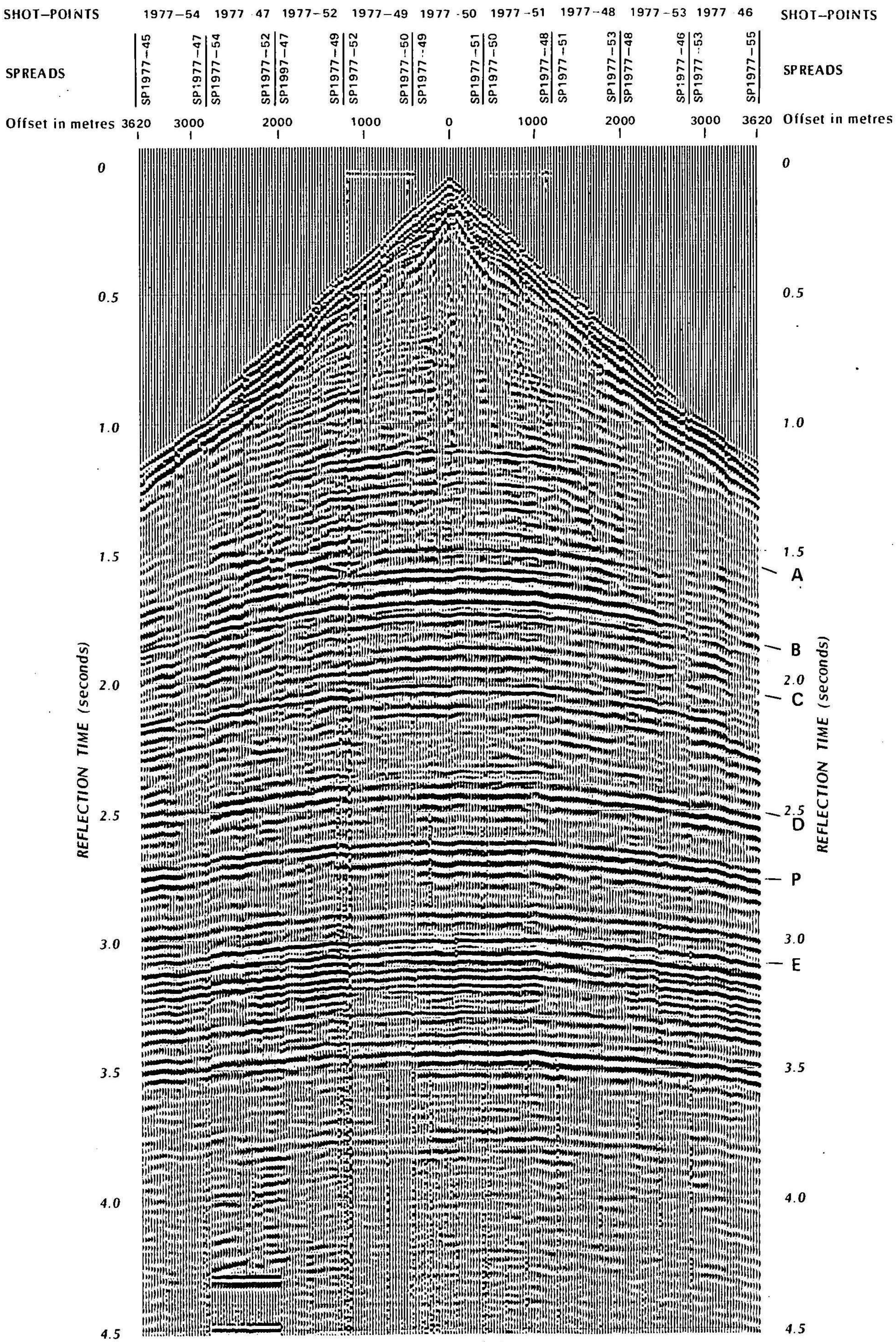
GOSSES BLUFF SEISMIC SURVEY, 1969

EXPANDED SPREAD GB/AB
centred on Traverse GB/A SP1021

F53/B3–172A

6

PLATE 6



To Accompany Record No. 1971/141

RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder : PMR-20

Amplifiers : PT-700

Prefilters : Out

Filters : L16 - KK135

AGC : S

Geophones : HS-J, 14Hz

Geophone Station Interval : 33.5m

Geophone Pattern :

16/trace in 2 rows of 8 in line
Rows 9m apart, geophones 6m apart

Shot Hole Pattern :

2 holes, 15m apart in line
Depth 20 - 26m
Commonest charge 2 x 45kg

PLAYBACK INFORMATION

Filters : LL20 - KK60

AGC : Off

Compositing : Nil

VELOCITY INFORMATION

Nil

HORIZONTAL SCALE

as indicated

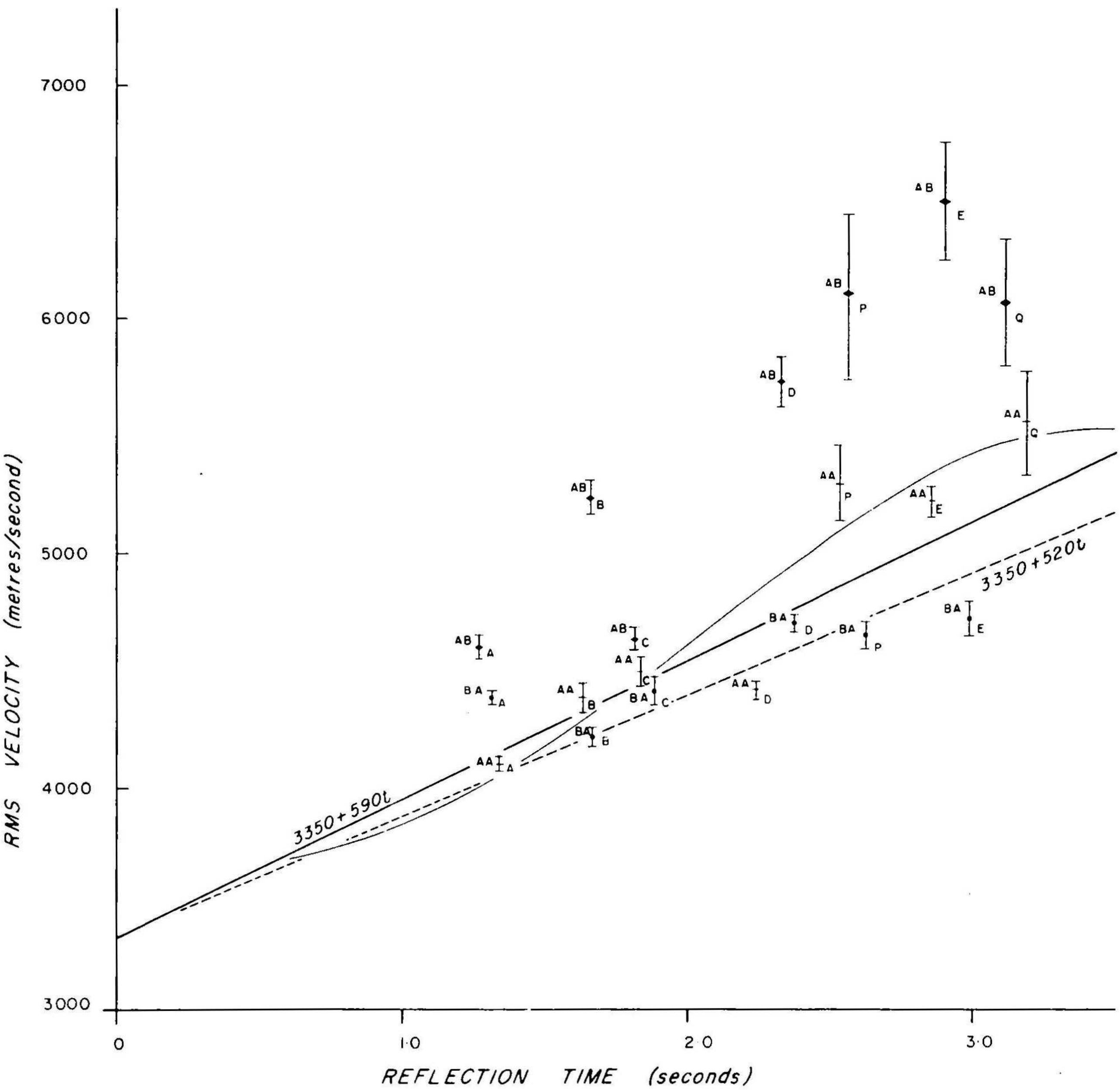
Note: Reflections identified are
those interpreted on Plates 13 and 14

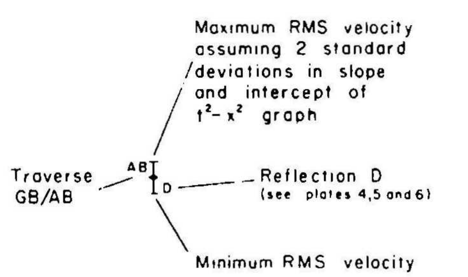
GOSSES BLUFF SEISMIC SURVEY, 1969

EXPANDED SPREAD GB/BA
centred on Traverse GB/B SP1977

F53/B3-173A

PLATE 7



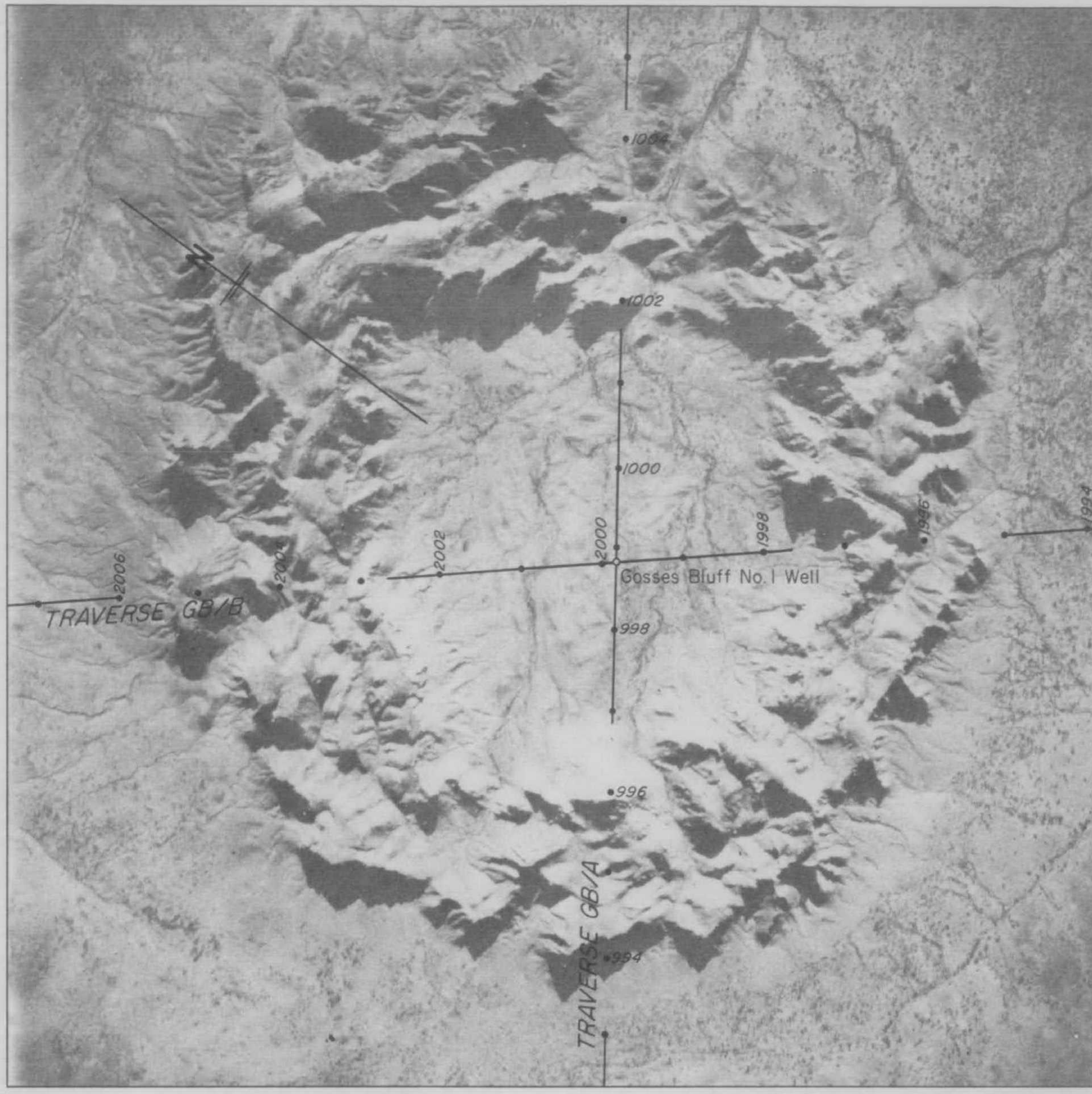


Velocity function deduced from t-Δt analysis on Traverse GB/B (SE)

RMS VELOCITY V REFLECTION TIME
Being results of Expanded Spreads
GB AA, GB AB & GB BA and t:Δt Analysis

To Accompany Record No. 1971/141

F53/B3-177A



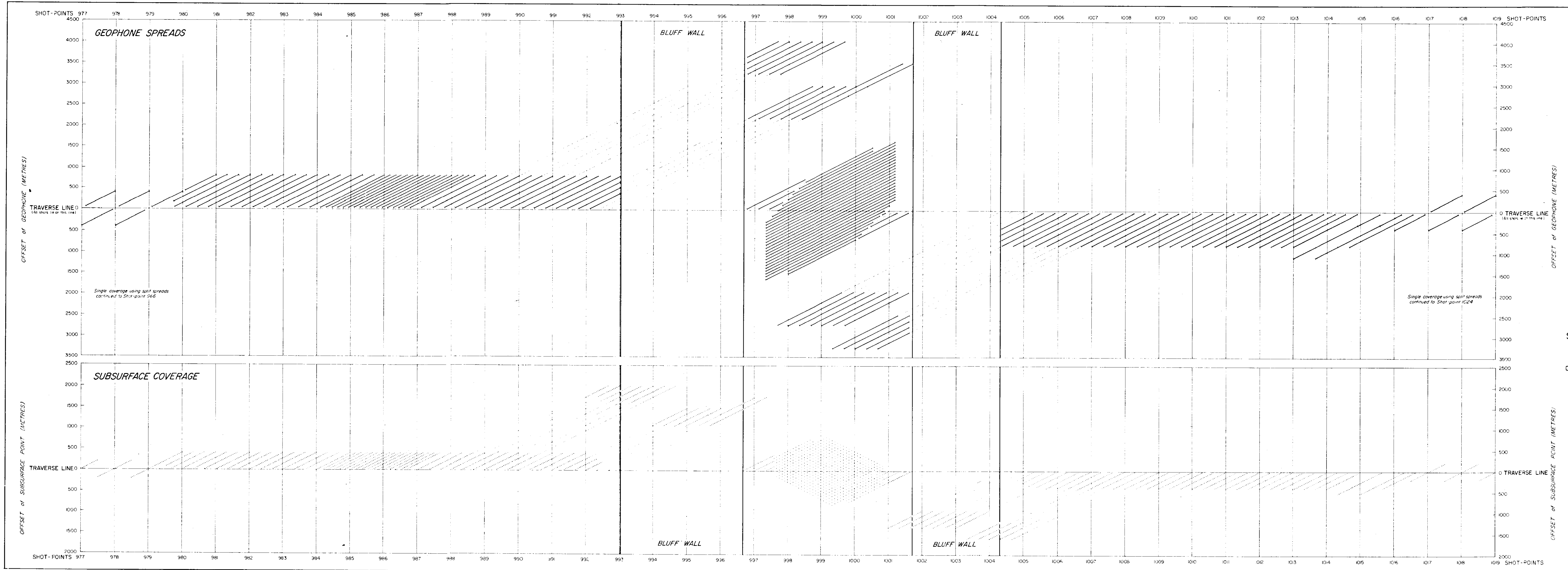
SCALE

METRES 0 500 1000 2000 3000 METRES

(APPROXIMATE)

—— *Parts of traverses accessible to seismic operations*

AERIAL VIEW OF GOSSES BLUFF
SHOWING POSITION OF SEISMIC TRAVERSES



GOSSES BLUFF

SEISMIC SURVEY, 1969

GEOPHONE SPREADS AND CORRESPONDING SUBSURFACE COVERAGE

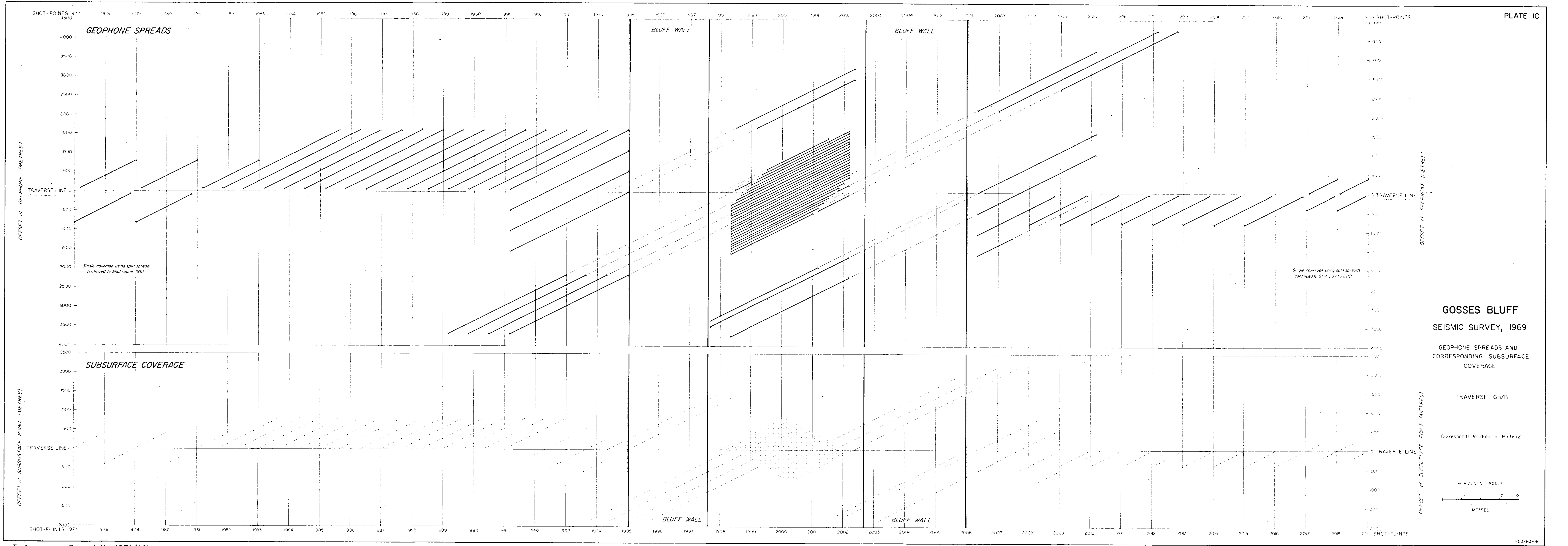
TRAVERSE G8/A

Corresponds to data on Plate 11

HORIZONTAL SCALE

METRES

To Accompany Record No. 1971/141



To Accompany Record No. 1971/141

PLATE 11

CORRECTED RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder: PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : L16 – KK135

Programmed Gain Function: A

Geophones: HS – J, 14Hz

Geophone Station Interval: 33.5m

PLAYBACK INFORMATION

Filters: LL20–KK60 or LL16–KK47

AGC : SS

VELOCITY INFORMATION

Expanded Spreads and Moveout Scans

HORIZONTAL SCALE
(metres)

0 250 500 750 1000

0 402 805

GOSSES BLUFF
SEISMIC SURVEY, 1969

TRAVERSE GB/A

OTHER RECORDING AND PROCESSING INFORMATION

Multiplicity of Coverage	Single	3 — 3 to 6	6 to 3 — 3	3-fold	12 to 24-fold 24 to 12	3-fold	3-fold	Single
Shot-hole Pattern	6 holes in 2 rows of 3 in line Rows 15m apart, holes 15m apart Depth 38–40m, commonest charge 6 x 7kg	6 holes in 2 rows of 3 in line Rows 15m apart, holes 15m apart Depth 25–26m, charge 6 x 7kg	3 holes, 15m apart in line Depth 24–26m or 29–31m Charge 3 x 14kg	3 holes, 15m apart in line Depth 20–26m Commonest charge 3 x 45kg	Single hole Depth 26–30m Charge 36kg	3 holes, 15m apart in line Depth 20–26m Commonest charge 3 x 45kg	3 holes, 15m apart in line Depth 23–26m Commonest charge 3 x 14kg	3 holes, 15m apart in line Depth 23–26m Commonest charge 3 x 14kg
Geophone Pattern	16/trace in 2 rows of 8 in line Rows 9m apart, geophones 6m apart	32/trace in 4 rows of 8 in line Rows 9m apart, geophones 6m apart		32/trace in 4 rows of 8 in line Rows 9m apart, geophones 5m apart	48/trace in 3 rows of 16 in line Rows 9m apart Geophones 5m apart	32/trace in 4 rows of 8 in line Rows 9m apart, geophones 5m apart	32/trace in 4 rows of 8 in line Rows 9m apart, geophones 6m apart	32/trace in 4 rows of 8 in line Rows 9m apart, geophones 6m apart
Digital Processing	None	None		30 point time – varying deconvolution			None	None
	LL20 – KK60	LL20 – KK60		LL16 – KK47			LL20 – KK60	

LL20 – KK60

To Accompany Record No. 1971/141

CORRECTED RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder: PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : L16 – KK135

Programmed Gain (2009 – 2017 AGC SS)

Function: A

Geophones: HS–1, 14Hz

Geophone Station Interval:

67.1m (1960 – 2009)
33.5m (2009 – 2029)

PLAYBACK INFORMATION

Filters LL20 – KK60 or LL16 – KK47

AGC : SS

VELOCITY INFORMATION

Expanded Spreads and Moveout Scans

HORIZONTAL SCALE
(metres)

0 250 500 750 1000
0 402 805

GOSSES BLUFF
SEISMIC SURVEY, 1969

TRAVERSE GB/B

OTHER RECORDING AND PROCESSING INFORMATION

Multiplicity of Coverage	Single	3 – fold	3 – fold	12 to 24–fold 24 to 12	3 – fold	Single	Single
Shot-hole Pattern	5 holes, 15m apart in line Depth 22–26m, Commonest charge 5 x 27kg	5 holes, 15m apart in line Depth 24–26m, Commonest charge 5 x 14kg	3 holes, 15m apart in line Depth 24–30m Commonest charge 3 x 45kg	Single hole Depth 26–30m Charge 36kg	3 holes, 15m apart in line Depth 20–26m, Commonest charge 3 x 45kg	5 holes, 34m apart transverse Depth 11–23m Charge 5 x 91kg 9 holes, 34m apart transverse Depth 14–23m Commonest charge 9 x 45kg	3 holes, 15m apart in line Depth 24–26m, Charge 3 x 14kg
Geophone Pattern	32/trace in 2 rows of 16 in line Rows 9m apart, Geophones 6m apart	32/trace in 2 rows of 16 in line Rows 9m apart, Geophones 6m apart	32/trace in 2 rows of 16 in line Rows 9m apart Geophones 6m apart	48/trace in 3 rows of 16 in line Rows 9m apart Geophones 6m apart	32/trace in 2 rows of 16 in line Rows 9m apart, Geophones 5m apart	32/trace, 3m apart transverse	32/trace in 4 rows of 8 in line Rows 9m apart, Geophones 6m apart
Digital Processing	None	None	30 point time – varying deconvolution				None
Playback Filter	LL20 – KK60	LL20 – KK60	LL16 – KK47				LL20 – KK60

To Accompany Record No. 1971/141

F53/B3–166

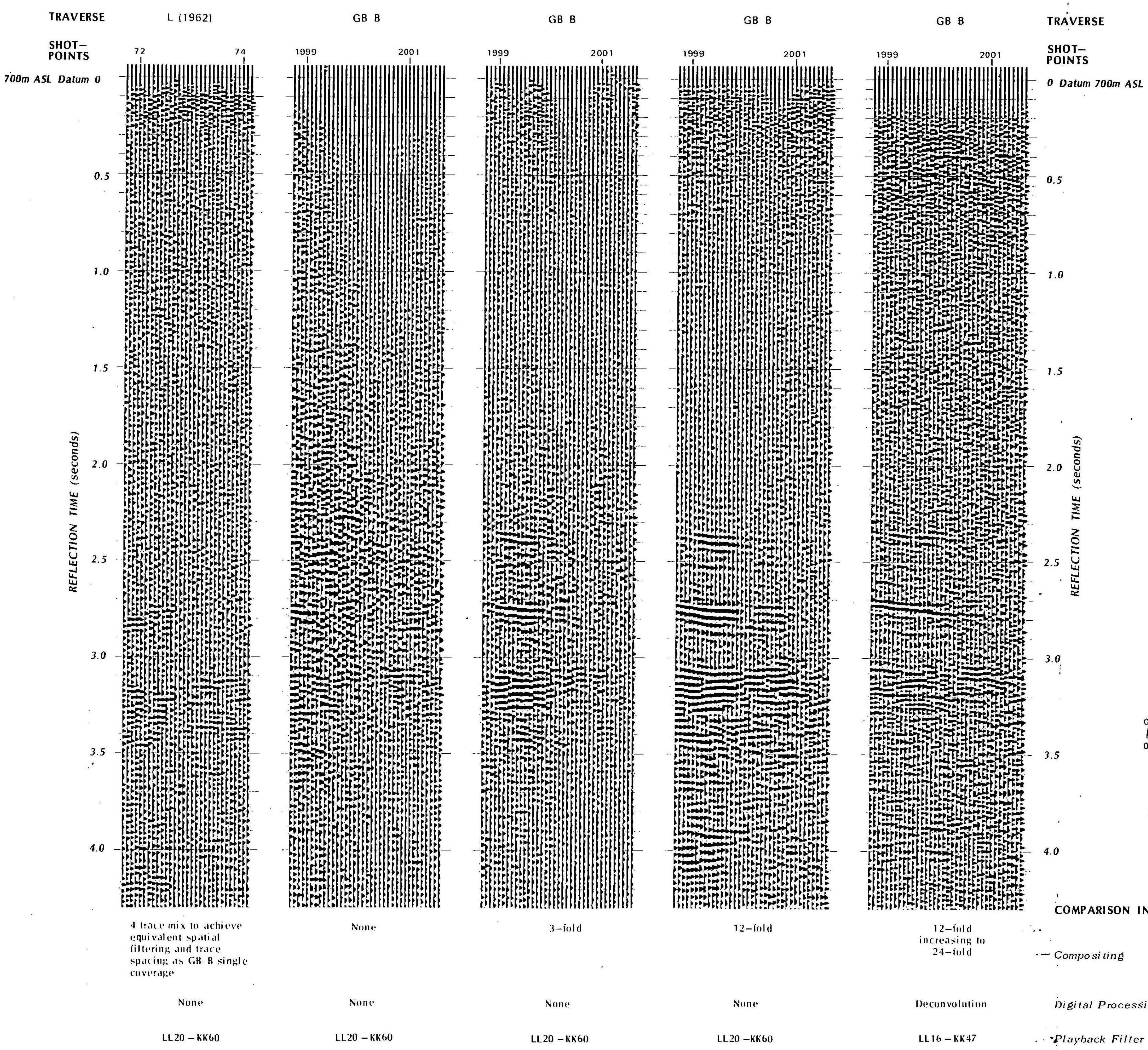
INTERPRETED RECORD SECTION
AND BOUGUER ANOMALY PROFILE

TRAVERSE GB/A

To Accompany Record No. 1971/141

F53/B3-187

To Accomony Record No. 1971/141



CORRECTED RECORD SECTION

RECORDING INFORMATION (Traverse GB/B only)

Magnetic Recorder : PMR–20

Amplifiers : PT–700

Prefilters : Out

Filters : L16 – KK135

Programmed Gain :

Function : A

Geophones : HS–J, 14Hz

Geophone Station Interval : 67.1m

Geophone Pattern :

48/trace in 3 rows of 16 in line
Rows 9m apart, geophones 6m apart

Shot Hole Pattern :

Single hole
Depth 26 – 30m
Charge 36kg

PLAYBACK INFORMATION

Filters : as indicated

AGC : SS

VELOCITY INFORMATION

Expanded Spreads and Moveout Scans

HORIZONTAL SCALE
(metres)

0 250 500 750 1000
0 402 805

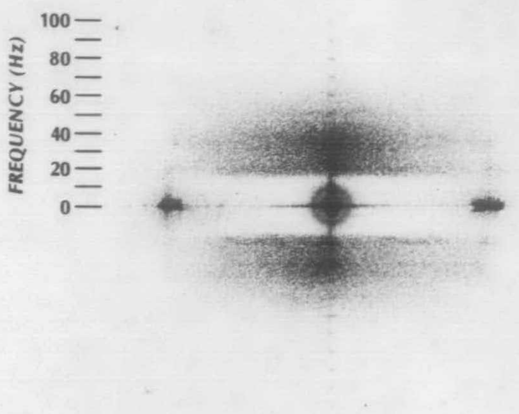
GOSSES BLUFF SEISMIC SURVEY, 1969

COMPARISON OF RECORDING AND PROCESSING TECHNIQUES INSIDE GOSSES BLUFF

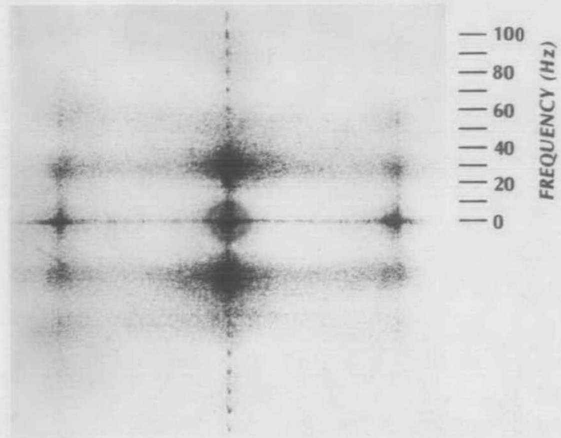
F53/B3–179

To Accompany Record No. 1971/141

PLATE 16

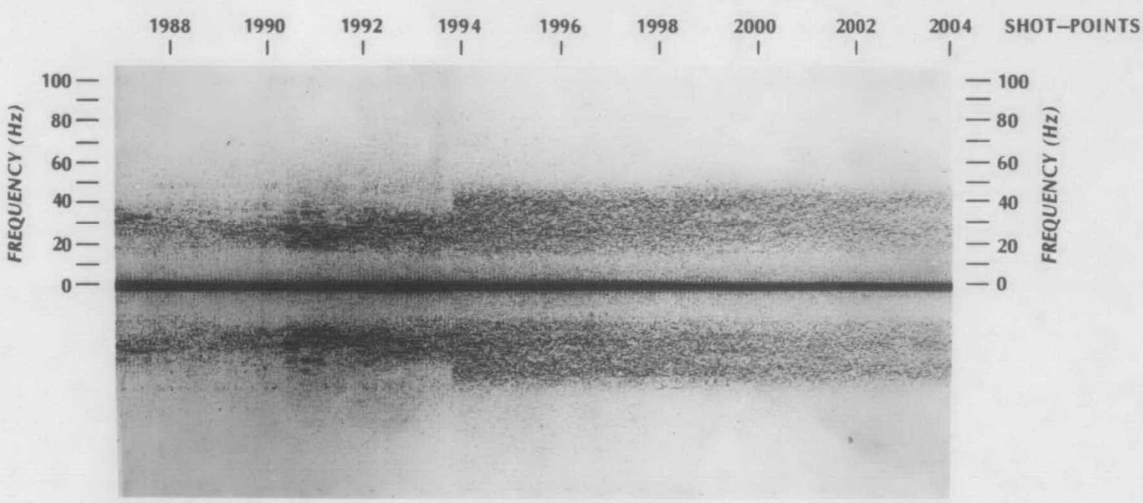


Traverse L (1962), SPs 79 – 95



Traverse GB/A, SPs 1007 – 1024

Two–dimensional Fourier Transform patterns of processed seismic sections from north of Gosses Bluff, showing reduction of random noise compared to 1962 survey data



Traverse GB/B

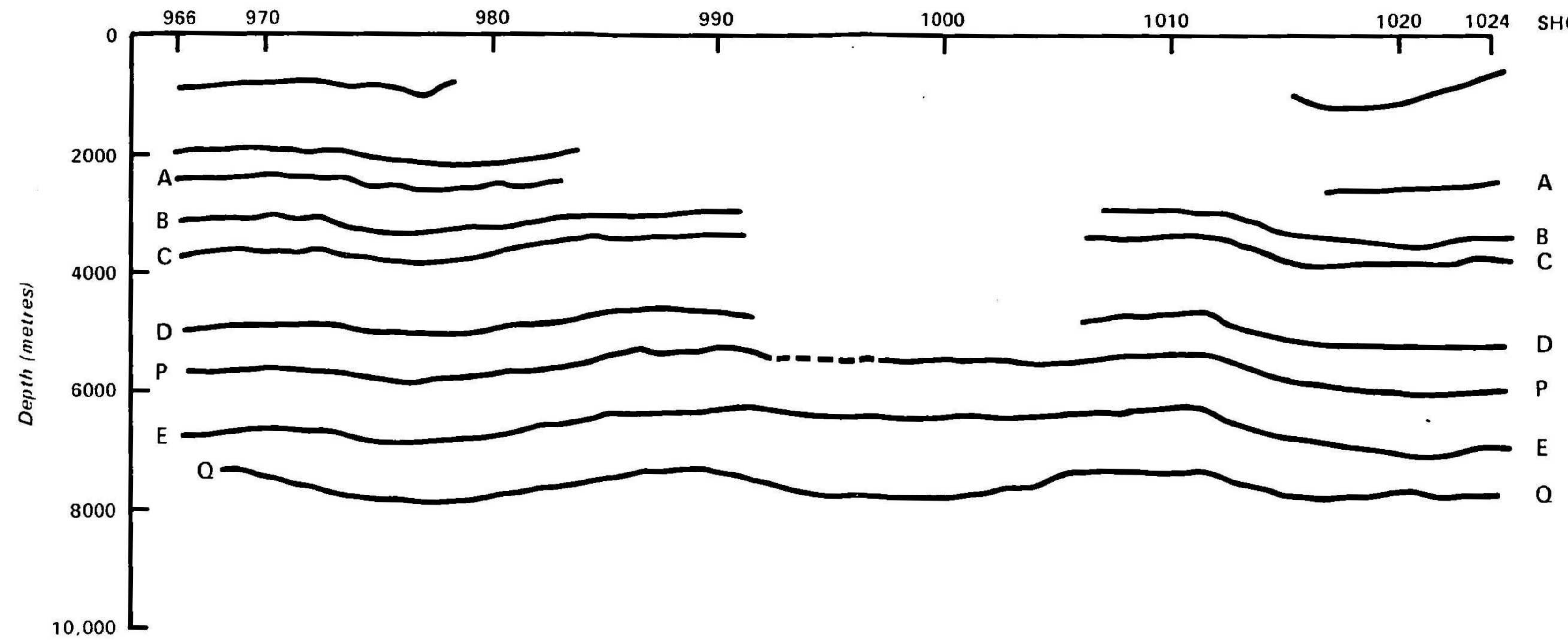
One–dimensional Fourier Transform pattern showing spectrum whitening effect of deconvolution to the right of SP 1994

GOSSES BLUFF SEISMIC SURVEY, 1969

LASERSCAN ANALYSIS
of processed seismic sections

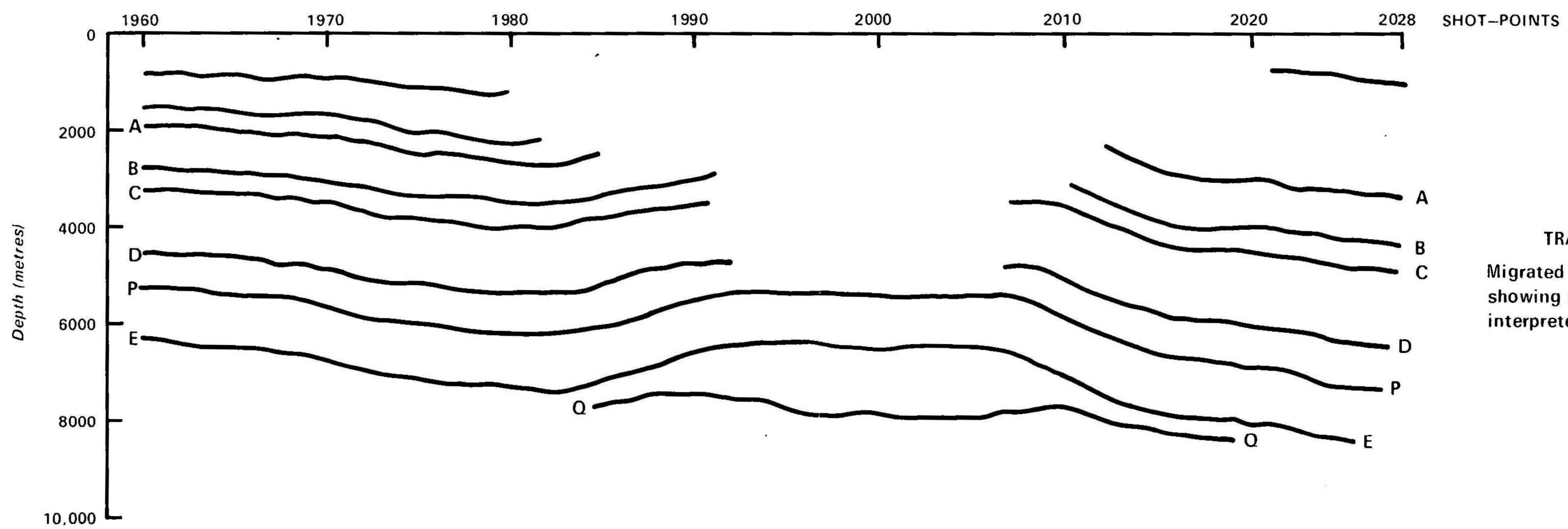
F53/B3–180A

PLATE 17



TRAVERSE GB/A

Migrated Depth Section showing seismic reflections interpreted on Plate 13



TRAVERSE GB/B

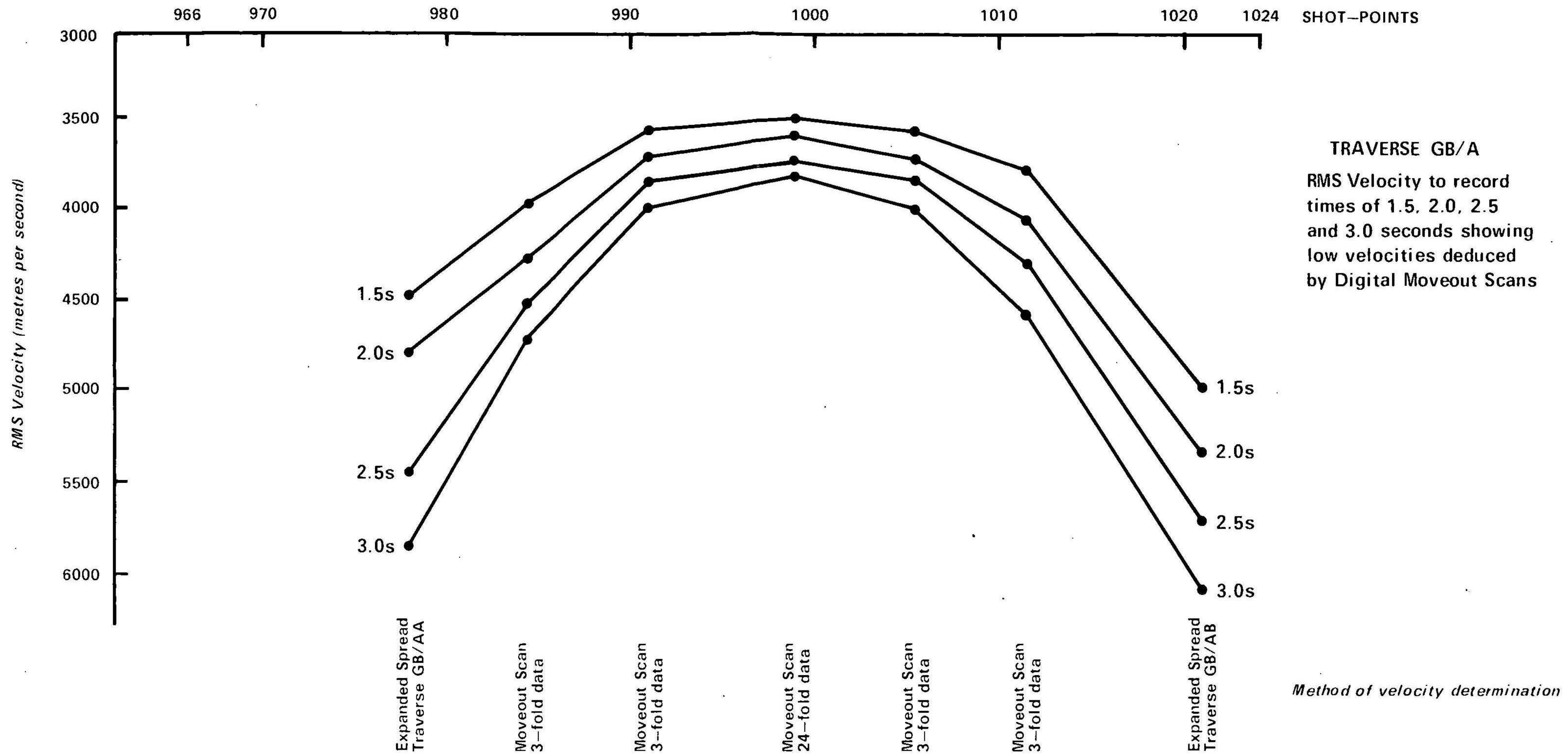
Migrated Depth Section showing seismic reflections interpreted on Plate 14

Average velocity function used:

V = 3350+590t

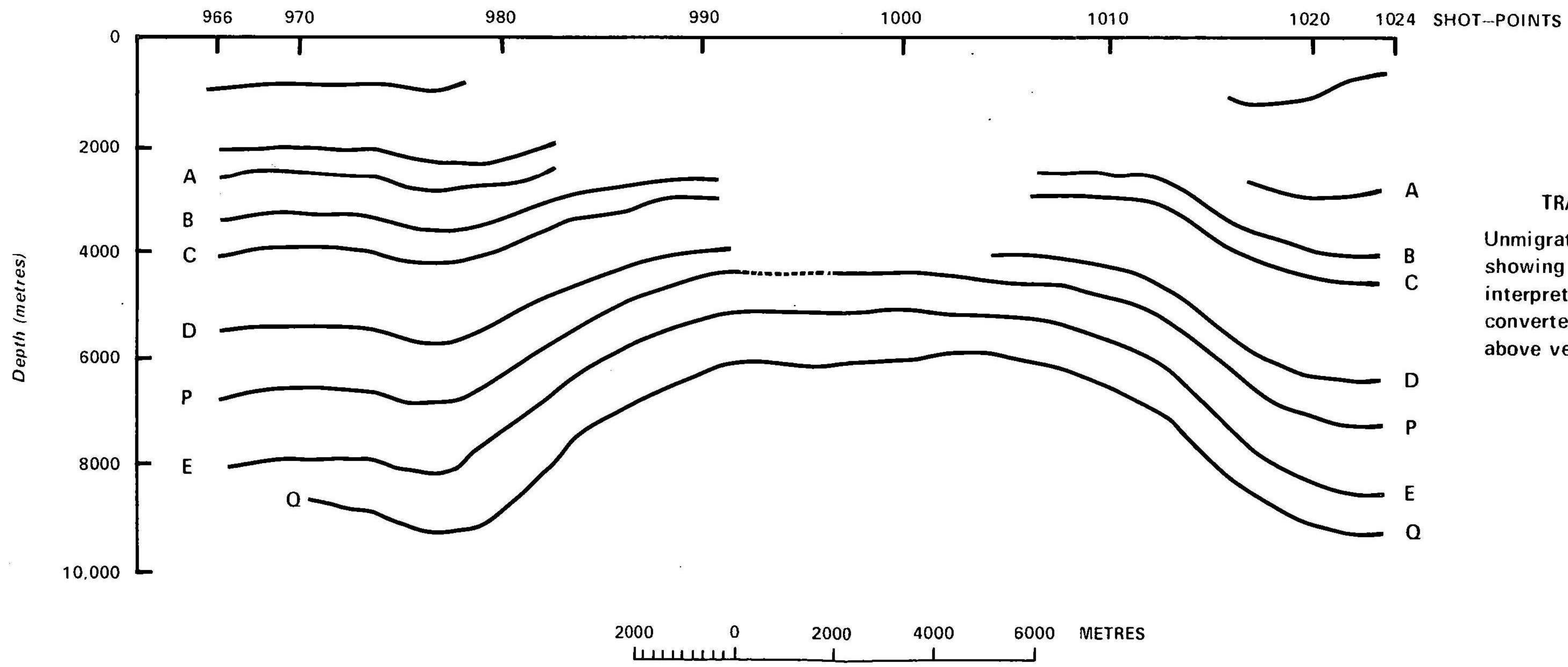
2000 0 2000 4000 6000 METRES

$\frac{V}{H} = 1$



TRAVERSE GB/A

RMS Velocity to record times of 1.5, 2.0, 2.5 and 3.0 seconds showing low velocities deduced by Digital Moveout Scans



TRAVERSE GB/A

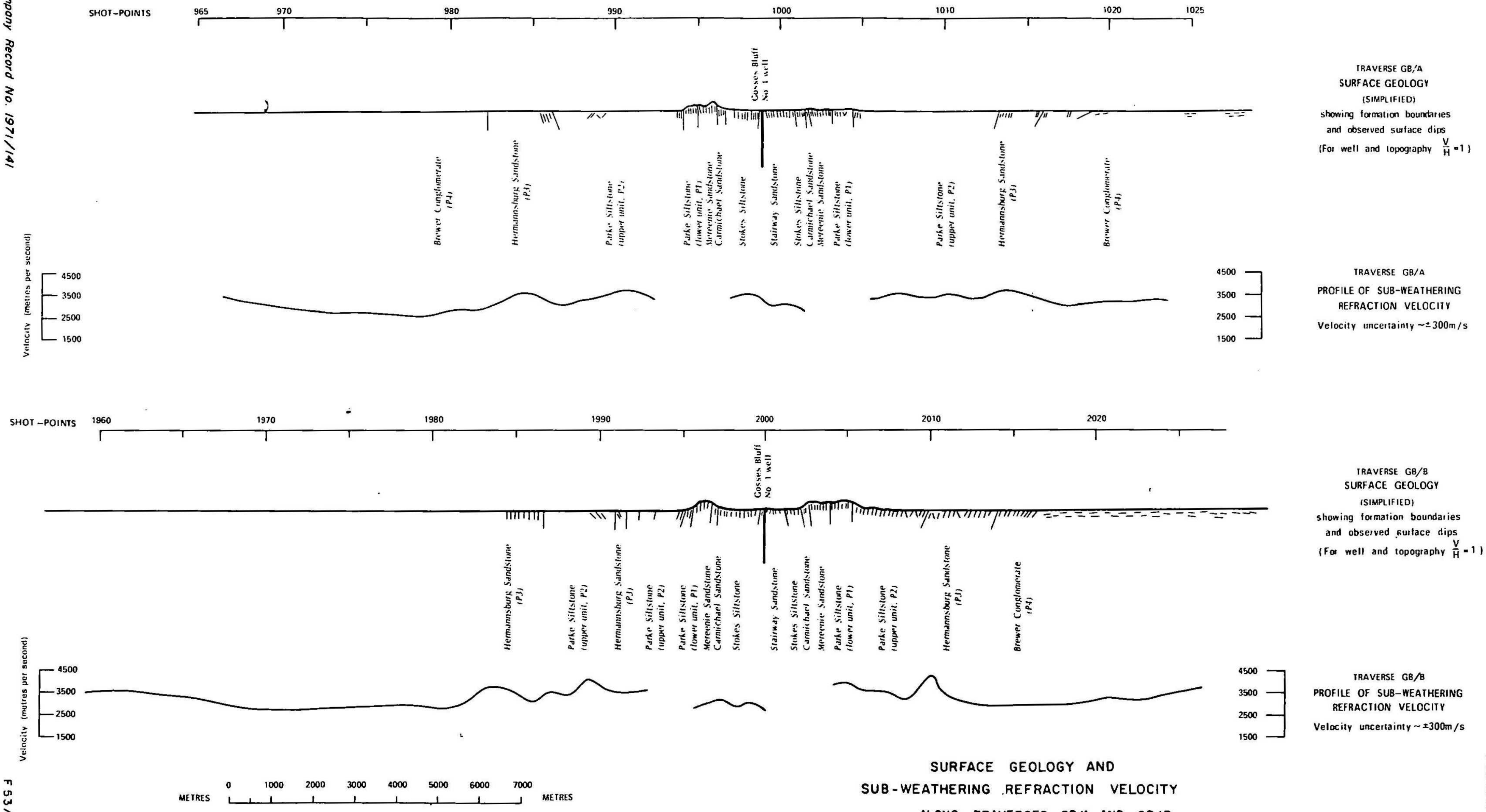
Unmigrated Depth Section showing seismic reflections interpreted on Plate 13 converted to depth using the above velocities

$\frac{V}{H} = 1$

To Accompany Record No. 1971/141

F53/B3-182

To Accompany Record No. 1971/141



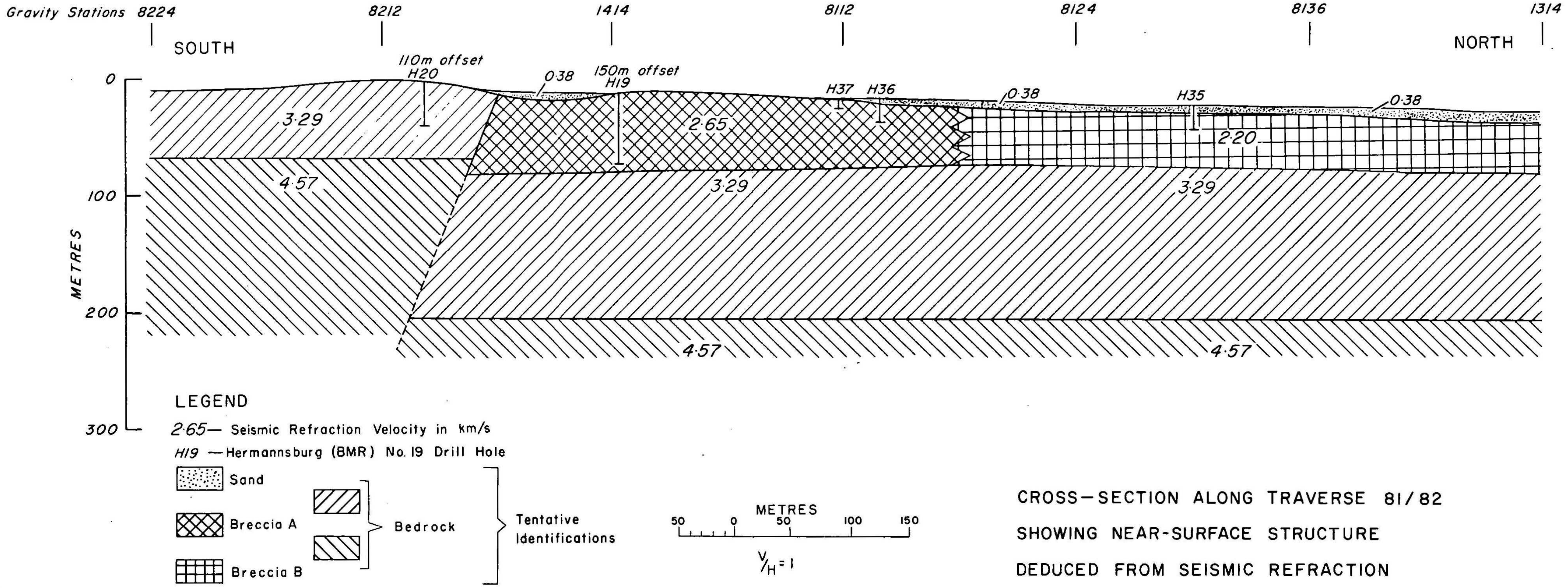
SURFACE GEOLOGY AND
SUB-WEATHERING REFRACTION VELOCITY
ALONG TRAVERSES GB/A AND GB/B

PLATE 19

F 53/B3-183 R


PLATE 20
GOSSES BLUFF SEISMIC SURVEY, 1969
PROBABLE CROSS-SECTION THROUGH GOSSES BLUFF ALONG TRAVERSE GB/B
Based on migrated seismic horizons (Plate 17) and surface geology (Plate 19)
SHOT-POINTS
1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028
Gosses Bluff No. 1 Well
SOUTHEAST
NORTHWEST
DEPTH (METRES)
0
1000
2000
3000
4000
5000
6000
7000
8000
Brewer Conglomerate (P4)
Hermannsburg Sandstone (P3)
Parke Siltstone (upper unit, P2)
Parke Siltstone (lower unit, P1)
Mereenie Sandstone
Carmichael Sandstone
Stokes Siltstone
Stairway Sandstone
Horn Valley Siltstone
Pacoota Sandstone
Goyder Formation
Jay Creek Limestone
Hugh River Shale
Arumbera Sandstone
Pertatataka Formation/ Areyonga Formation
Bitter Springs Formation
Heavitree Quartzite
Arunta Complex
P2
P3
P2
PERTNJARA GROUP
MEREENIE SANDSTONE
LARAPINTA GROUP
PERTAOORRTA GROUP
UPPER PROTEROZOIC
BASEMENT
A
B
C
D
P
Q
E
KILOMETRES
1 0 1 2 3 4
V/H = 1
LEGEND
Seismic Horizon
Formation Boundary
Formation disrupted
To Accompany Record No. 1971/141
F53/B3-174-2

PLATE 21

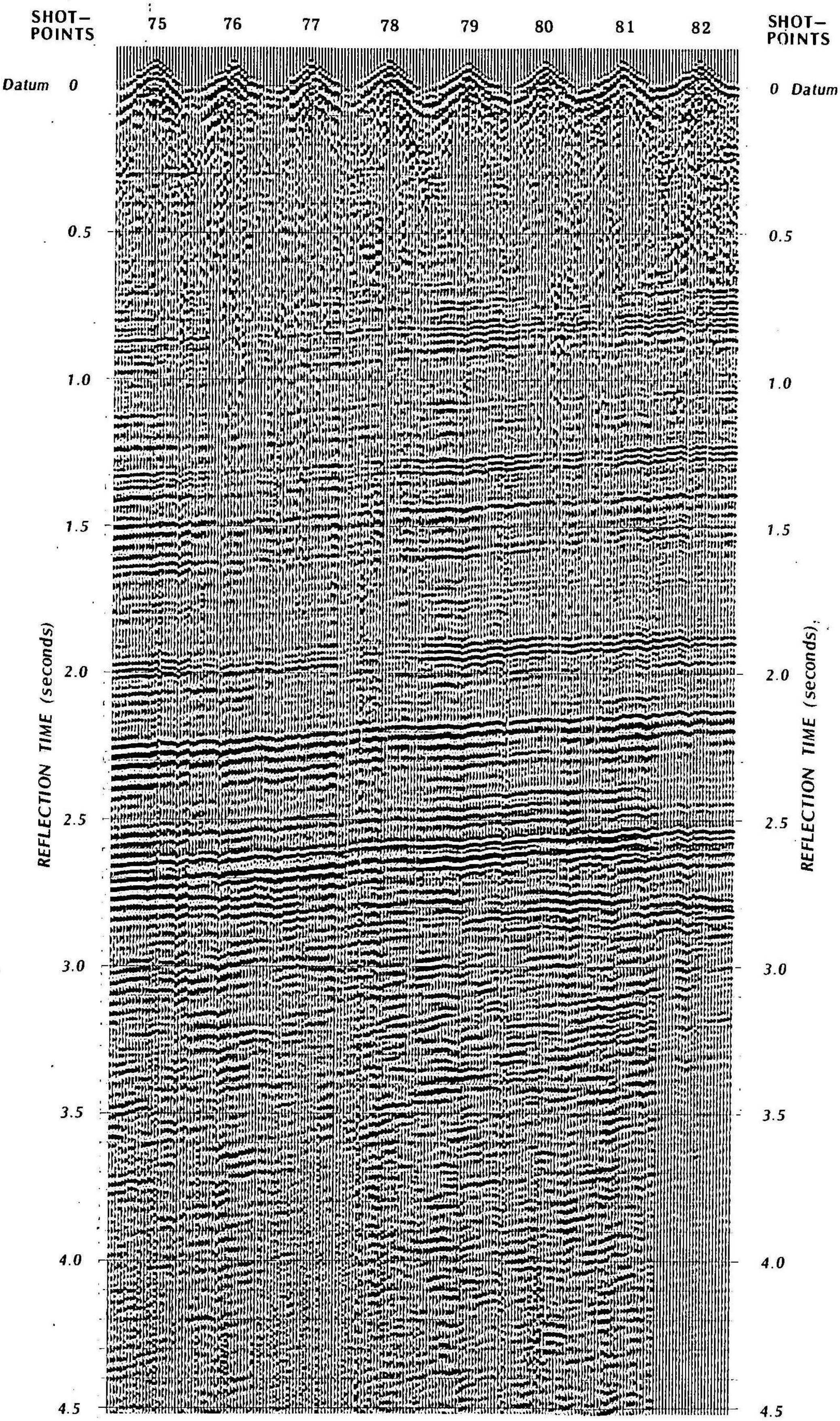


CROSS—SECTION ALONG TRAVERSE 81/82 SHOWING NEAR-SURFACE STRUCTURE DEDUCED FROM SEISMIC REFRACTION

To Accompany Record No. 1971/141

F53/B3-178

PLATE 22



To Accompany Record No. 1971/141

CORRECTED RECORD SECTION

RECORDING INFORMATION

Magnetic Recorder : PMR-20

Amplifiers : PT-700

Prefilters : Out

Filters : L16 – KK135

AGC : M

Geophones : HS-J, 14Hz

Geophone Station Interval : 45.8m

Geophone Pattern :

8/trace, 6m apart in line

Shot Hole Pattern :

2 holes, 15m apart in line
Depth 21–26m
Commonest charge 2 x 34kg

PLAYBACK INFORMATION

Filters : LL20 – KK78

AGC : Off

Compositing : Nil

VELOCITY INFORMATION

Expanded Spread, Traverse L, 1962

HORIZONTAL SCALE
(metres)

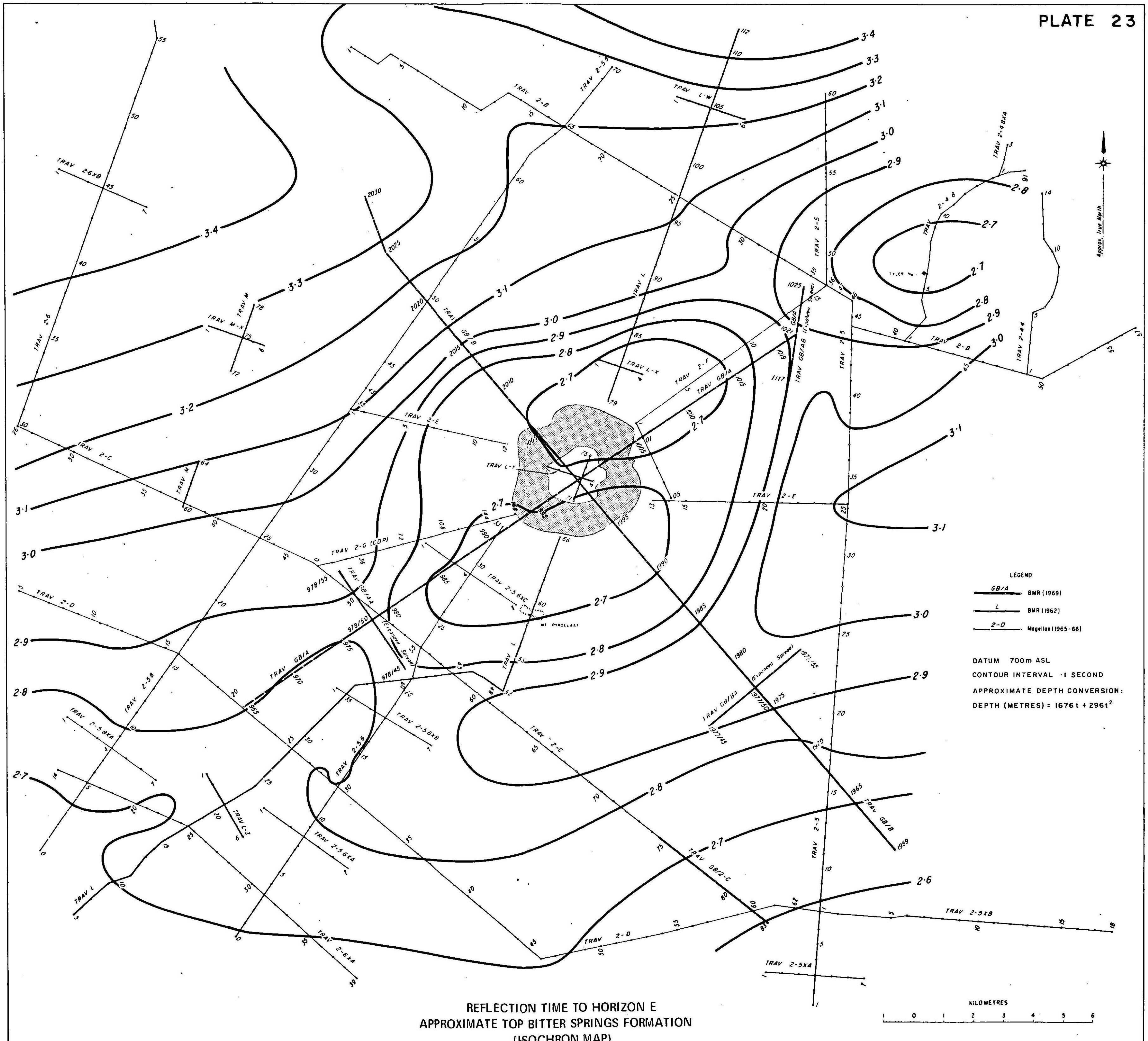
0 500 1000 1500
0 548 1096 1644

GOSSES BLUFF SEISMIC SURVEY, 1969

TRAVERSE GB/2-C

F53/B3-168A

PLATE 23

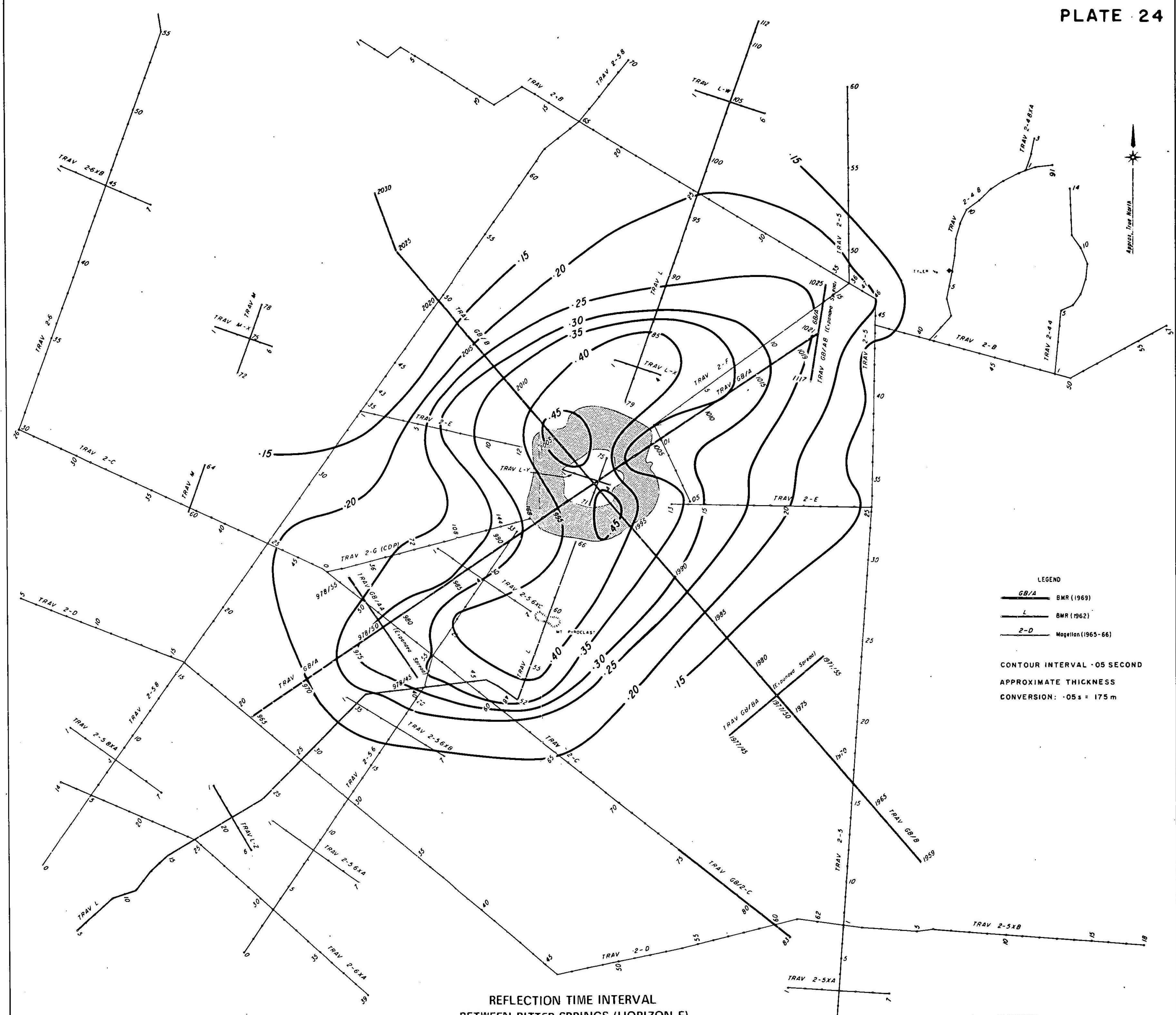


REFLECTION TIME TO HORIZON E
APPROXIMATE TOP BITTER SPRINGS FORMATION
(ISOCHRON MAP)

To Accompany Record No. 1971/141

F53/B3 — 176

PLATE 24



REFLECTION TIME INTERVAL
BETWEEN BITTER SPRINGS (HORIZON E)
AND BASEMENT REFLECTIONS
(ISOPACH MAP)

To Accompany Record No. 1971/141

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