ST. MAGNUS BAY, SHETLAND: A PROBABLE BRITISH METEORITE CRATER OF LARGE SIZE

ALAN W. SHARP

Dept. of Astronomy, University of Manchester, England

(Received 17 March, 1970)

Abstract. The last two decades have witnessed a continually expanding programme of investigation concerned with the discovery of terrestrial impact craters or 'astroblemes' as Dietz has called them. These are the wounds produced on the Earth's surface by the high speed collisions with giant meteorites which have taken place throughout geological time. With the exception of a few comparatively recent craters, most of the large scars originated tens or hundreds of millions of years ago and have been preserved as 'fossils' in rocks which have since undergone considerable erosion and alteration.

Although various workers have now gathered an impressive array of evidence appertaining to the topographical, petrological and mineralogical changes wrought by the sudden release of enormous quantities of energy when collisions occur, it still remains true that most discoveries of craters are made as a result of their quasi-circular appearance on maps or aerial photographs.

A search of maps of the British Isles has revealed several possible impact sites, of which the most convincing is the feature known as St. Magnus Bay in the Shetland Islands. No explanation other than massive impact seems able to account for the peculiar shape of the bay and its resemblance to certain ancient Canadian impact crater residuals.

In size it ranks among the dozen or so largest terrestrial impact features and is thus an important object for further study; in its own right and in the context of the currently enhanced speculation concerning the origin of craters on such bodies as the Moon and Mars.

1. Introduction

During the twenty years which have elapsed since the recognition of the Chubb meteorite crater in Canada by V. B. Meen of the Royal Ontario Museum in 1950, an increasing effort has been put into the search for the terrestrial equivalents of the many impact features which scar the surfaces of the Moon and Mars and presumably those of the other similar small bodies in the Solar System, too.

Progress has been so rapid that Bunch and Short (1968), in a paper read to the First Congress on Shock Metamorphism of Natural Materials, at the Goddard Space Flight Centre in April 1966, were able to list over fifty sizeable features on Earth which could reasonably be ascribed to collision with large fragments of extra-terrestrial matter. The great majority of these craters, forty-five, being in excess of half a mile or 0.8 km diameter, with the largest, Manicouagan, scaling nearly 40 miles or 60 km and thus equalling in size the well-known lunar crater, Eratosthenes.

Still larger impacts have been invoked to account for the enormous Bushveldt igneous complex in Africa and the 90 miles (144 km) radius Nastapoka Islands arc in Hudson Bay, said to bear a strong resemblance to a part of Mare Crisium. (Beals *et al.*, 1963).

Subsequent to the Conference, Svensson, of the Swedish Geological Survey, has

The Moon **2** (1970) 144–156.

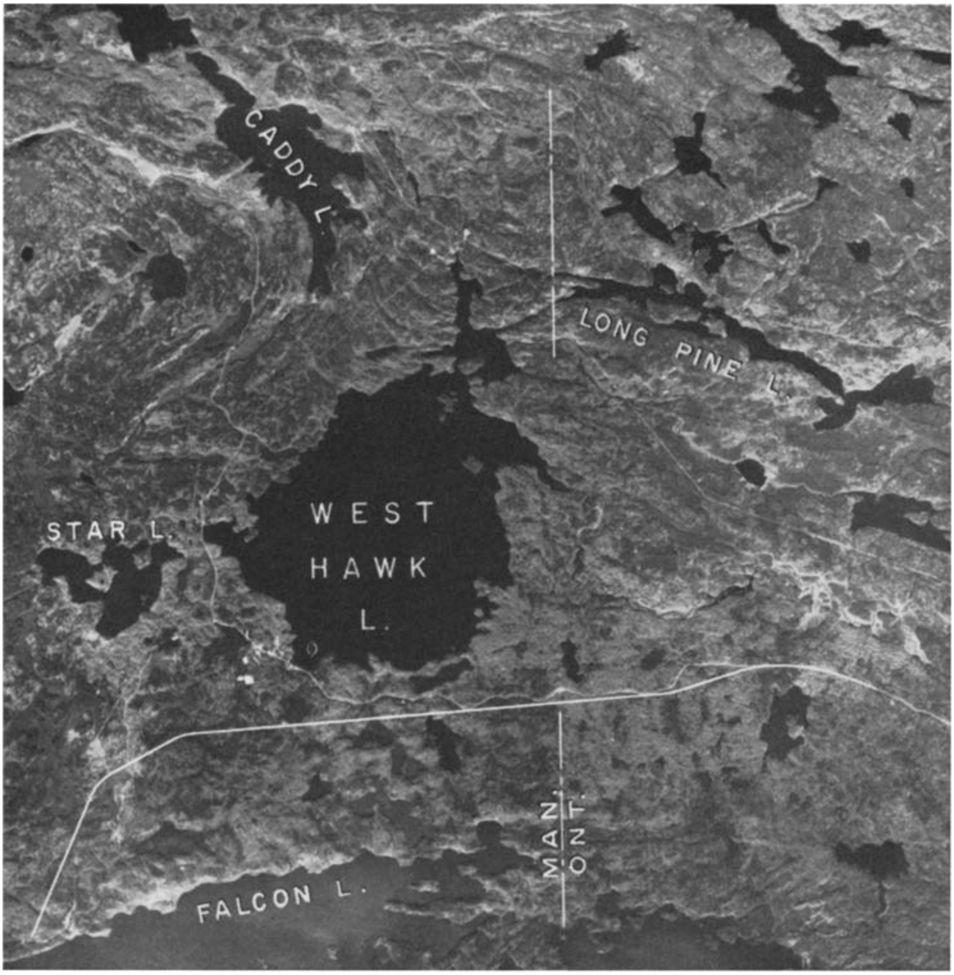

Fig. 1. Air photograph of West Hawk Lake, Manitoba, Canada. Courtesy, Dominion Observatory, Ottawa, Canada.

proposed several 'new' craters in Scandinavia; the most impressive being the Siljan Ring in central Sweden whose diameter is given by Beals and Halliday (1967) as 22 miles or 35 km, a rather conservative estimate. Another large new crater is named after Lake El'Gytkhyn in the U.S.S.R.

Most of these big impact scars have been described as 'fossil' (Beals *et al.*, 1963), in the sense that they have been preserved in the rocks for hundreds of millions of years and hence no longer display their pristine forms due to the erosion and change which affect the rocks of the Earth's crust and any objects embedded within them.

Consequently, it has become necessary to develop criteria which will serve to distinguish impact features from those of a non-impact origin.

2. Mechanism of Large Crater Formation

When a giant meteorite strikes the ground at cosmic speed the whole of its kinetic energy must be dissipated in an extremely short interval of time, thus producing an explosion of incredible violence, comparable to that of a powerful atomic device (cf. Dence *et al.*, 1965).

The net result is akin to that which would be produced by a very high brisance explosion of similar energy at some point not far below ground level called the effective centre of burst.

Nuclear test explosions provide useful sources of comparison and indicate the sorts of energies with which one is dealing. The Teapot Ess crater was about 300 ft (90 m) in diameter and resulted from an energy release equivalent to 1.2 kT of T.N.T. indicating that the comparable Oesel crater, Kaalijärv, could have been caused by a nickel iron meteorite ten to a dozen ft (3–4 m) in diameter travelling at about 10 miles per second (16 k.p.s.).

The 800 ft (240 m) Burton-on-Trent ammunition dump crater required only a slightly greater expenditure of energy than did the Odessa No. 1 meteorite crater, namely about 15 kT.

By comparison the 4000 ft (1200 m) diameter Barringer crater needed something like one megaton equivalent which could have been provided by a nickel iron meteorite 130 ft (40 m) in diameter travelling at 10 miles per second (16 k.p.s.).

Of course, the actual speed is unknown and may have been slightly less than this, in which case a larger diameter would have been necessary (Sharp, 1969) or the converse. Nininger (1952) has suggested that two separate bodies were involved, each of them being about 100 ft (29 m) in diameter at the speed assumed above. The writer, however, regards the double impact theory as introducing an unnecessary complication.

If the single body case is considered for the moment and a 260 ft (77 m) effective depth of burst below original ground level, the time taken for penetration was in the region of one fiftieth of a second, during which much of the meteorite and the ground through which it moved was converted into a fiery gaseous mass which then exploded to form the crater. The exact mechanism was doubtless extremely complicated and comprised mechanical deformation plus explosive scouring by the impact fireball.

The mechanical deformation produced the lens of breccia below the true crater floor and fracturing of the basement rock beneath the breccia. The sideways forces caused buckling of the rock strata which underlie the crater rim, whilst the explosive expansion of the pent-up gases eviscerated the bowl of the crater and distributed fragments in the vicinity, some of which enhanced the height of the rim whilst others fell back into the crater itself.

A certain amount of the meteorite was injected into the rock substance of the crater floor and now resides there in the form of globules of nickel-iron. Larger fragments of iron, not melted or vaporized in the impact have been discovered outside the crater along with many thousands of tons of condensed metallic spherules.

Over the course of millions of years even large craters become worn down by erosion and the more obvious characteristics such as the presence of meteoric iron are no longer available to render diagnosis easy. In such cases it becomes necessary to resort to more subtle techniques of analysis such as gravity and magnetic surveys, examination of drill cores and so forth in order to prove or disprove an impact origin. The costs involved rise very sharply to levels which place a limit on the speed with which new investigations can be commenced and many probable impact sites must await confirmation until the necessary resources become available.

Nevertheless, the results of many complex studies have proved that sophisticated methods are eminently worthwhile, especially when applied to some of the largest structures so far investigated. These include West Hawk Lake (Figure 1) diam 1.6 miles (2.6 km), the Deep Bay of Reindeer Lake (Figure 2), (diam 6.5 miles or 10.4 km), Carswell Lake (diam 18 miles or 29 km), the Clearwater Lakes (Figure 3) (diams 14 and 20 miles, 22 and 32 km) and Manicouagan Lake (diam 38–40 miles, 60–64 km), all of which have been prospected by the new methods and shown to have an impact origin.

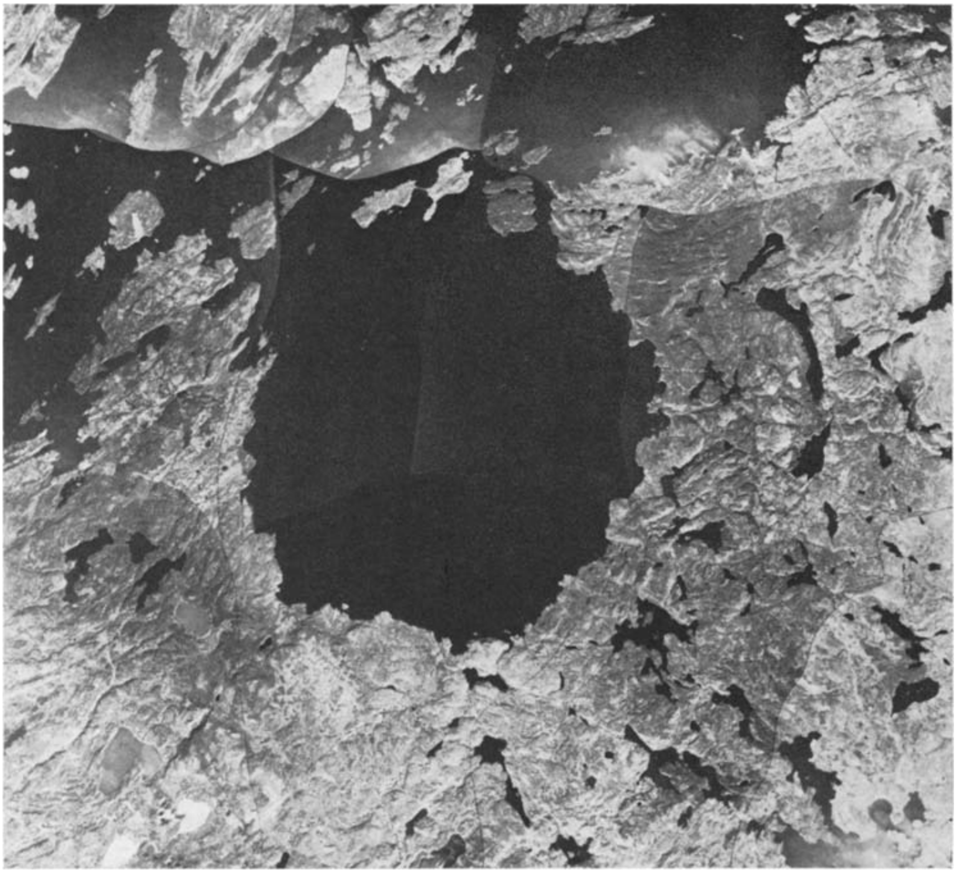

Fig. 2. Aerial photograph of the Deep Bay of Reindeer Lake, Saskatchewan, Canada. Courtesy, Dominion Observatory, Ottawa, Canada.

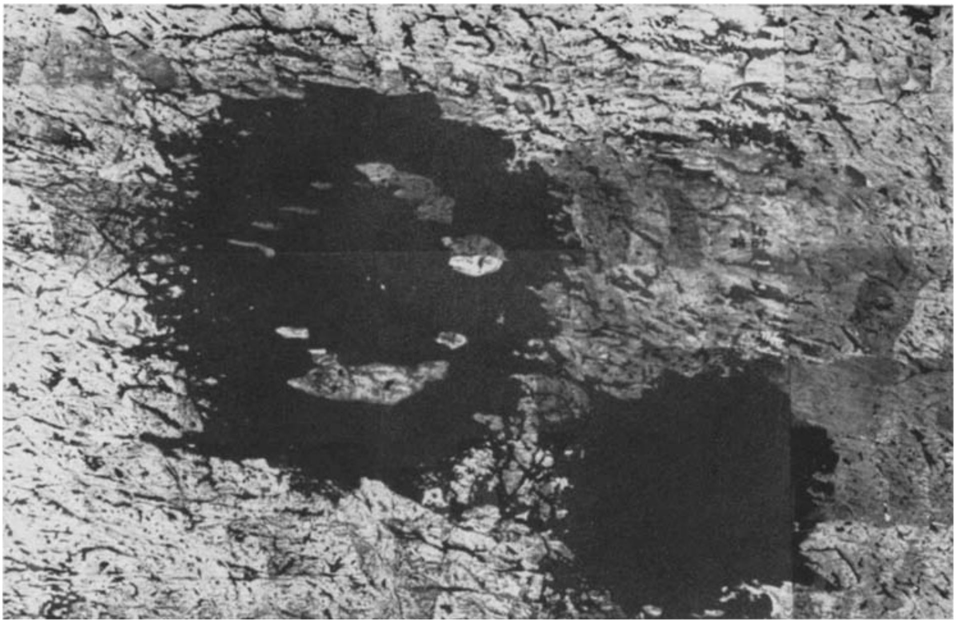

Fig. 3. Aerial photograph of the Clearwater Lakes, Canada, showing the central ring of islands in the larger lake. The islands are formed of a lava-like impact breccia overlying shattered gneiss, as are the central parts of the smaller lake. Courtesy, Dominion Observatory, Ottawa, Canada.

In addition, the presence of immense volumes of what might be described as impact lava has been proved at the Manicouagan and Clearwater Lakes sites, to mention but two, and show that sufficient heat was generated during impact to melt substantial quantities of the original rocks which have subsequently been mistaken for truly volcanic material.

Much of the available energy of impact is, in fact, deployed in the form of intense shock waves, and the complex changes to which these give rise in the rocks at the impact site include shock deformation of crystals, shatter cone production, brecciation, melting and the formation of high-pressure mineral phases such as coesite, stishovite and diamond.

These effects provide the confirmatory evidence which must be sought at any suspected impact locality, if necessary by the drilling of boreholes and the extraction of drill cores for laboratory examination.

The most important single feature of any impact scar is, however, its shape and it is this aspect which has led to the detection of many impact sites by the study of maps and aerial photographs.

3. St. Magnus Bay, Shetland

An examination of a map of the British Isles shows a quasicircular indentation on the west coast of the mainland of Shetland (Lat. 60° 25′ N, Long. 1° 34′ W). It is

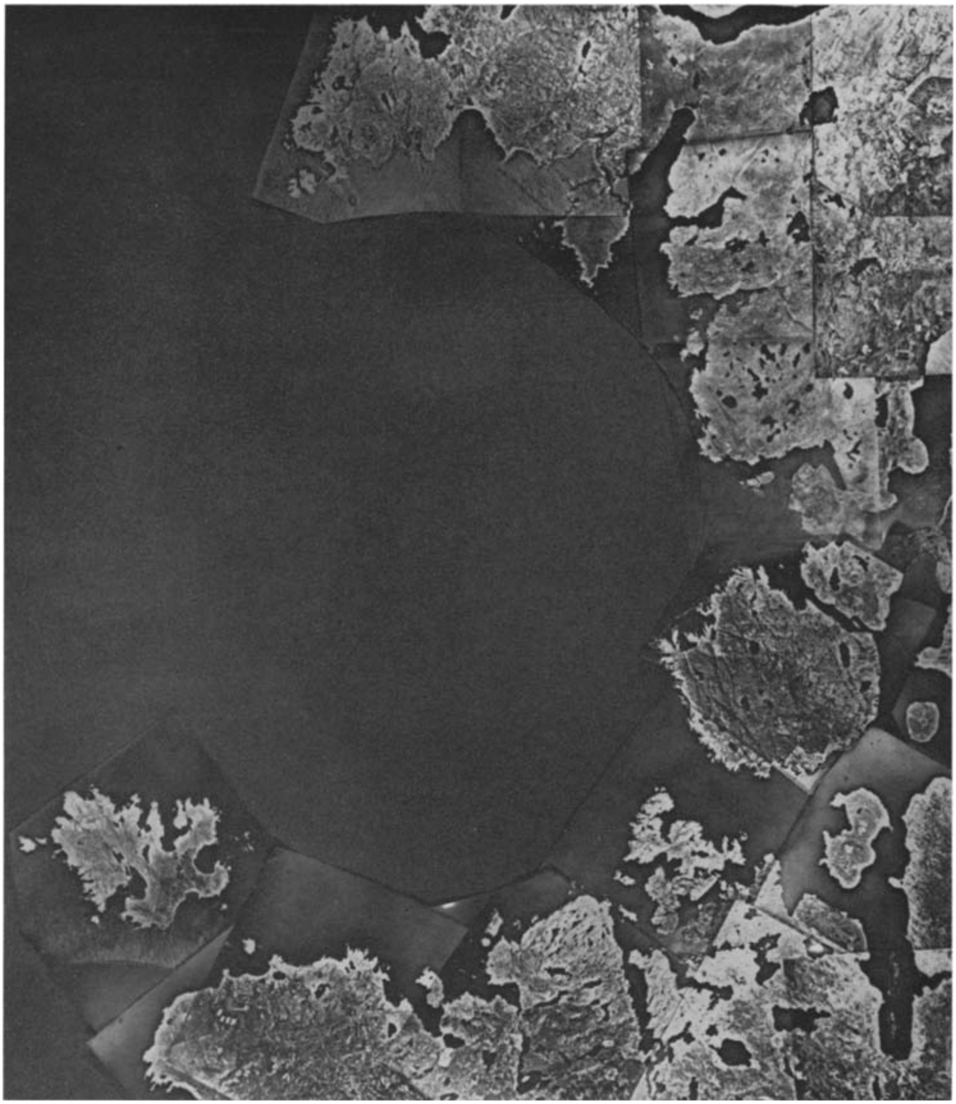

Fig. 4. Aerial photograph mosaic of St. Magnus Bay, Shetland Islands, Great Britain. Crown Copyright Ordnance Survey Photograph. Reproduced by permission of the Controller of H. M. Stationery Office.

called St. Magnus Bay (Figure 4) and has a mean diameter of approximately ten miles (16 km). Furthermore, reference to the bathymetric charts of the area elicits the additional information that the circle is completed underwater by a discontinuous ridge delineated by the fifty fathom contour (Figure 5). This ridge effects closure between the Esha Ness promontory on the north and the island of Papa Stour to the west of the bay.

The feature so formed may owe its shape to a post-Devonian impact crater of large size which reached down into what is now the central region of St. Magnus Bay and whose subsequent erosion has given us the present topography. The crater probably had a diameter of about seven miles (11 km) and a depth of 3000–3500 ft (900–1100 m) (cf. Baldwin, 1963), whilst below this was a breccia lens over a mile in maximum thickness underlain by a zone of fractured rock extending down several thousand feet

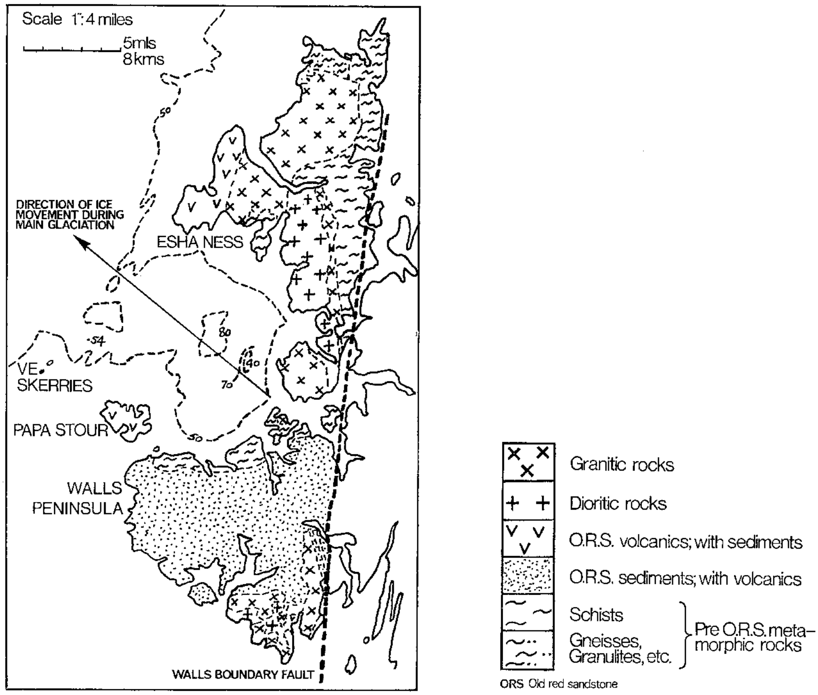

Fig. 5. Geological and hydrographic map of St. Magnus Bay, Shetland. Maximum depth of water along underwater ridge, 54 fathoms, 320 ft or 97 m. Maximum depth of water in bay, 90 fathoms, 540 ft or 160 m. Contours in fathoms, interpolated from spot depths by the author, who accepts full responsibility for any inaccuracies. Hydrographic data reproduced from British Admiralty charts Nos. 1118a and 1118b with the sanction of the Controller, H. M. Stationery Office and the Hydrographer of the Navy.

further below the surface. Such a crater could have been produced by the impact of a small asteroid, one third of a mile (0.5 km) in diameter, travelling at about ten miles a second or by one of 350 yards (310 m) diameter travelling at 25 miles per second, (40 km per second), using Baldwin's formulae (Baldwin, 1963, p. 170) for the sizes of iron meteorites. The diameters of stony meteorites would have been about 30% greater than the above values.

Unfortunately the geology of Shetland is extremely complex (Wilson *et al.*, 1929–34) due to the position of the Islands in the centre of the old Caledonian mobile belt, and this fact enhances the difficulty of proving or disproving the impact nature of the topographical feature under discussion. The geology is important, however, for its apparent failure to explain the peculiar shape of St. Magnus Bay.

For present purposes the local rocks can be divided as follows (Wilson and Knox, 1936):

(a) Several groups of metamorphic rocks of pre-Devonian age.

(b) Overlying sedimentary strata referable to the Old Red Sandstone (c) Contemporaneous acid and basic volcanic material also of Old Red Sandstone age. (d) Massive intrusions of granitic and other rocks, generally regarded as late Devonian.	Approximate age 350 million years, plus.

(e) Other intrusives.

(f) Glacial deposits of Pleistocene age.

Several major dislocations traverse the mainland of Shetland, in particular the great Boundary Fault which cuts off the western region from the rest of the islands, geologically speaking, and runs close to the eastern edge of St. Magnus Bay. The shatter belt associated with this fault displays obvious weakness in resisting erosion. There is, in addition, some evidence of radial fracturing in the vicinity of the bay which tends to support the impact hypothesis, although many of the lineaments are obviously independent of the bay.

In geologically recent times, glaciation of the Islands has been intense (Peach *et al.*, 1879) and has resulted in substantial erosion and glacial overdeepening. Thick ice from Scandinavia changed direction over the Shetlands and moved down into St. Magnus Bay from the S.E., probably accounting in large measure for the central 90 fathom (160 m) depression, the non-circularity of the 50 fathom (90 m) contour and the 200 ft high step. (Figure 5). It may also partly account for the threshold-like nature of the submerged ridge south of Esha Ness, though reference to the magnetic anomaly map (Figure 6) indicates that a structural line of some importance lies here and separates areas having markedly different magnetic anomaly patterns (McQuillin *et al.*, 1967). It is most unlikely, though, that glacial erosion was itself responsible for the circular outline of St. Magnus Bay, and in this connection it is interesting to note that an 80 fathom depression exists off the east coast of Shetland but is not near the centre of any obvious circular coastal indentation. The writer considers it to have an essentially glacial origin.

The gravity anomaly map of the St. Magnus Bay area (Figure 7) shows, like the magnetic map, an intimate dependence on the geology and topography, but the contours terminate too far from the centre of the bay to have much diagnostic value. They neither confirm nor deny the impact hypothesis, or any other. The same may be said about the magnetic data themselves, though there is a slight broadening of some of the magnetic contours in the centre of the bay and a tendency for extremes to congregate round the periphery, which may indicate a smoothing out of the magnetic intensity beneath the presumed centre of impact.

As Beals has remarked (Beals, 1964): "Recent studies suggest that there is no single

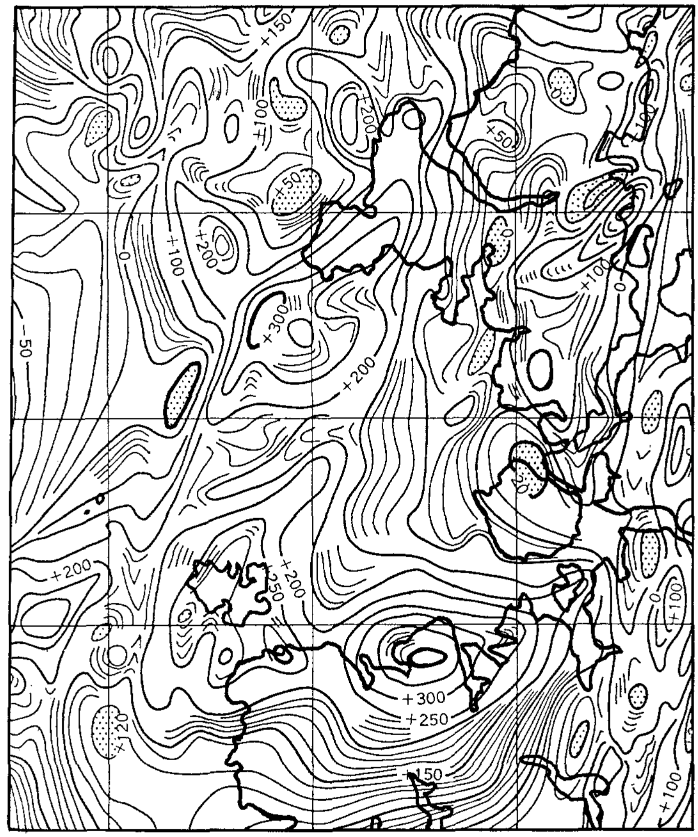

Fig. 6. Magnetic total force anomaly map of St. Magnus Bay, Shetland. Contours in gammas above a linear field equation for the British Isles. Crown Copyright Geological Survey map. Reproduced by permission of the Controller of H. M. Stationery Office.

clear-cut and unambiguous interpretation of magnetic anomalies associated with meteorite craters." Each one must therefore be dealt with on its merits.

Gravity data, on the other hand, are apparently more amenable to persuasion, and deviations over the bay may be derived from the Bouguer anomalies – when these become available – by making suitable allowances for local topographical and geological features (Halliday *et al.*, 1963). Hence it becomes vitally important that gravity data for the bay be secured at the earliest opportunity. Seismic data, too, will be very valuable.

The St. Magnus Bay feature is cross-cutting with relation to the Devonian rock formations and hence is post-Devonian in date. It is clearly affected by glaciation and hence is pre-Pleistocene. Its state of preservation is such as to suggest a late Palaezoic or early Mesozoic age (Dence, 1969). It is reminiscent in many ways of the Deep Bay, Lac Couture, East Clearwater Lake and other craters in Canada and may have possessed a slight central uplift (Dence *et al.*, 1968).

Fig. 7. Gravity map of Bouguer anomalies, St. Magnus Bay, Shetland Islands. Contours at 1 mgal and 5 mgal intervals. Crown Copyright Geological Survey map. Reproduced by permission of the Controller of H. M. Stationery Office.

It is possible on an impact basis that St. Magnus Bay contains at least 500 ft (150 m) of sediments above a thick breccia lens (Figure 8) and that the latter is completely or almost completely obscured, except possibly in the vicinity of the 'step'.

In the absence of drill cores from within the fifty fathom contour and seismic or gravity data for the bay itself, the best hope of definitive information at present seems to lie in the discovery of boulders or pebbles of ice-transported impact breccia at the extreme south-westerly part of the Esha Ness promontory. Nevertheless, the fact that impact breccia, containing fragmented and shock metamorphosed allochthonous material, has been found in the vicinity of similar features elsewhere (French *et al.*, 1968), indicates that there is a strong possibility of its discovery in Shetland despite the generally unfavourable direction of ice movement.

The additional presence at Esha Ness of sedimentary erratics not known otherwise from the immediate vicinity of the bay, if such can be found, would tend to indicate a preserved post-impact fill whose discovery would narrow down the age range for the presumed crater. It would also enhance the claim for a meteoritic origin of the bay, since such a filling has been postulated as likely on the impact hypothesis.

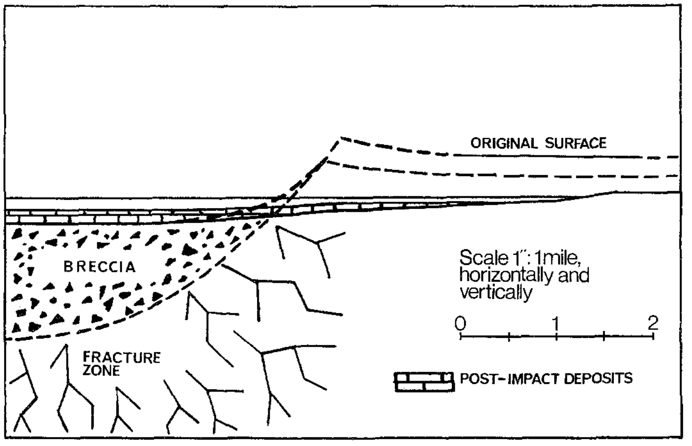

Fig. 8. North-South profile through the northern part of St. Magnus Bay, assuming a 7 mile (11 km) diameter impact crater.

The present evidence for an impact origin can be summarised as follows:

(a) The shape of St. Magnus Bay in plan view and in cross section.
(b) The general resemblance of the bay to other surface features of proved meteoritic origin and similar degree of preservation.
(c) The marked depression near the centre.
(d) The cross-cutting nature with respect to local geological formations.
(e) The lack of any obvious reason for the production of the quasi-circular outline by differential erosion.
(f) The presence of peripheral fractures and several arcuate lakes reminiscent of some at Deep Bay.
(g) The comparatively small variation in magnetic intensity over the central part of the bay when compared with the anomalies produced by the surrounding country rocks.
(h) The lack of a convincing alternative explanation.

The question of St. Magnus Bay as a meteoritic crater residual has been mooted on several occasions recently, in particular at the Liverpool meeting of the Meteor Section of the British Astronomical Association in September 1969, which the author addressed on the subject of Terrestrial Meteorite Craters and Cryptovolcanic Structures.

Various other quasi-circular landforms in Britain have been investigated as possible crater remnants, in particular St. Bride's Bay in Pembrokeshire (Lat. 51° 48′ N., Long. 5° 15′ W) but this, though glaciated, fails to show a central depression or good seaward closure and is fairly well ascribed to the differential erosion of soft strata belonging to the Carboniferous coal measures.

The writer has also looked at a Siljan Ring-like group of lakes in central Ireland without as yet finding any evidence for a meteoritic origin. Other 'circular' features are currently under scrutiny.

Unfortunately, British geologists in the main are not well informed about the subject of massive impact and frequently display scepticism verging on antagonism when the matter is raised. For instance, one well-known expert on Dalradian geology, the Shetlands in particular, recently informed the writer that the mineralogical criteria deduced by 'the Americans' as evidence for impact were 'rubbish' and could be duplicated by specimens of (ordinary) Shetland rocks.

The matter is raised here because such an attitude is not helpful when it comes to the procurement of funds for work on possible fossil impact craters and without funding such programmes as diamond drilling and seismic investigation are unlikely to materialise.

The more publicity and discussion which take place, therefore, the better the prospects for a thorough examination of the site.

Regarding St. Magnus Bay the writer considers that the odds are strongly in favour of a meteoritic origin, but that much rests on the application of the latest techniques for fossil crater recognition if definitive confirmation is to be obtained.

The bay probably owes its shape to a massive impact some 200–300 million years ago when the land surface was 1500–2000 ft (300–400 m) above the rocks currently exposed to view at sea level. Subsequent erosion has removed the crater rim and eaten back from the remains of the original structure, which has, however, exercised a guiding control in determining the present shape of St. Magnus Bay.

Acknowledgement

To M. R. Dence, Dominion Observatory, Ottawa, Canada, for generous encouragement and advice.

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