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14. New Observations at the Slate Islands Impact Structure, Lake Superior

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INTRODUCTION

Slate Islands, a group of 2 large and several small islands, is located in northern Lake Superior, approximately 10 km south of Terrace Bay. Shatter cones, breccias and shock metamorphic features provide evidence that the Slate Islands Structure was formed as a result of asteroid or comet impact (Halls and Grieve 1976, Grieve and Robertson 1976). Most of the island group is believed to represent the central uplift of a complex impact crater. The structure possibly has a diameter of about 32 km. For Sage (1978, 1991) shock metamorphic features, shatter cones and pervasive rock brecciation are the results of diatreme activity.

The present investigations represent the second year of a co-operative study of the Lunar and Planetary Institute, Houston, Texas and the Field Services Section (Northwest) of the Ontario Geological Survey. The objective of this investigation is to come to a better understanding of the formation of mid-size impact structures on Earth and the planets of the solar system. Impact processes played a fundamental role in the formation of the planets and the evolution of life on Earth. Meteorite and comet impacts are not a phenomenon of the past. Last year, more than 20 pieces of the Shoemaker–Levy 9 impacted on Jupiter and the Tunguska comet impacted in Siberia in the early years of this century. The study of impact processes is a relatively young part of geoscience and much is still to be learnt by detailed field and laboratory investigations.

The Slate Islands Structure has been selected for the present detailed investigations because of the excellent shoreline outcrops of rock units related to the impact. The structure is a complex impact crater that has been eroded so that important lithological and structural elements are exposed. We know of no other mid-size terrestrial impact structure with equal or better exposures.

In this publication we present preliminary results of our 1994 and 1995 field and laboratory investigations. We have tentatively identified a few impact melt and a considerable number of suevite occurrences. "Bunte Breccia" and "suevite" (for definitions see Engelhardt 1990 and references therein) and other clastic matrix breccias occur on the islands. (For names of specific locations mentioned in this publication please see Figure 14.1.)

GENERAL GEOLOGY OF SLATE ISLANDS

A wide variety of Archean and Proterozoic rocks underlie the islands. Archean rocks make up the bulk of the Slate Islands bedrock (Sage 1991). They are composed of greenschist facies, felsic to mafic pyroclastic rocks, pillowed and variolitic mafic flows, feldspar porphyry flows interbedded with mudstones, siltstones and ironstones. Archean gabbros and quartz-feldspar porphyries intrude the supracrustal rocks (Sage 1991).

Laminated argillite and chert-carbonate-hematite ironstone of the Gunflint Formation and argillite of the Rove Formation, both of the Animikie Group, as well as, mafic metavolcanic rocks, intraflow sandstone and siltstone, and diabase dikes of the Osler Group, Keweenawan Supergroup, occur on the islands but spatially are of limited extent (Sage 1991). Lamprophyres occur on the islands and one dike at the southeast coast of Patterson Island has been dated by the U-Pb method on perovskite at about 1.1 Ga (oral communication L.Heaman, University of Alberta, Edmonton, Alberta, 1994). This dike is cut by breccias (R.Sage, Ontario Geological Survey, Sudbury, oral communication 1994) believed to be related to the Slate Islands impact event. This date provides a maximum radiometric age for the impact. However, we have observed breccias on the islands containing sandstone and siltstone clasts that strongly resemble units of the Jacobsville Formation, suggesting a maximum age of about 800 ma, based on assignment of the Jacobsville Formation as Hadrynian (Card et al. 1994).

We did not attempt to reinterpret the distribution of the various Archean and Proterozoic rock units that underlie the island group. It is, however, worth noting that all rocks on the islands are brecciated to various degrees. Large rock masses on Mortimer and Delaute islands are monomict breccias and we have observed granitic rocks and diabase on Patterson Island that easily break into centimetre-sized angular fragments

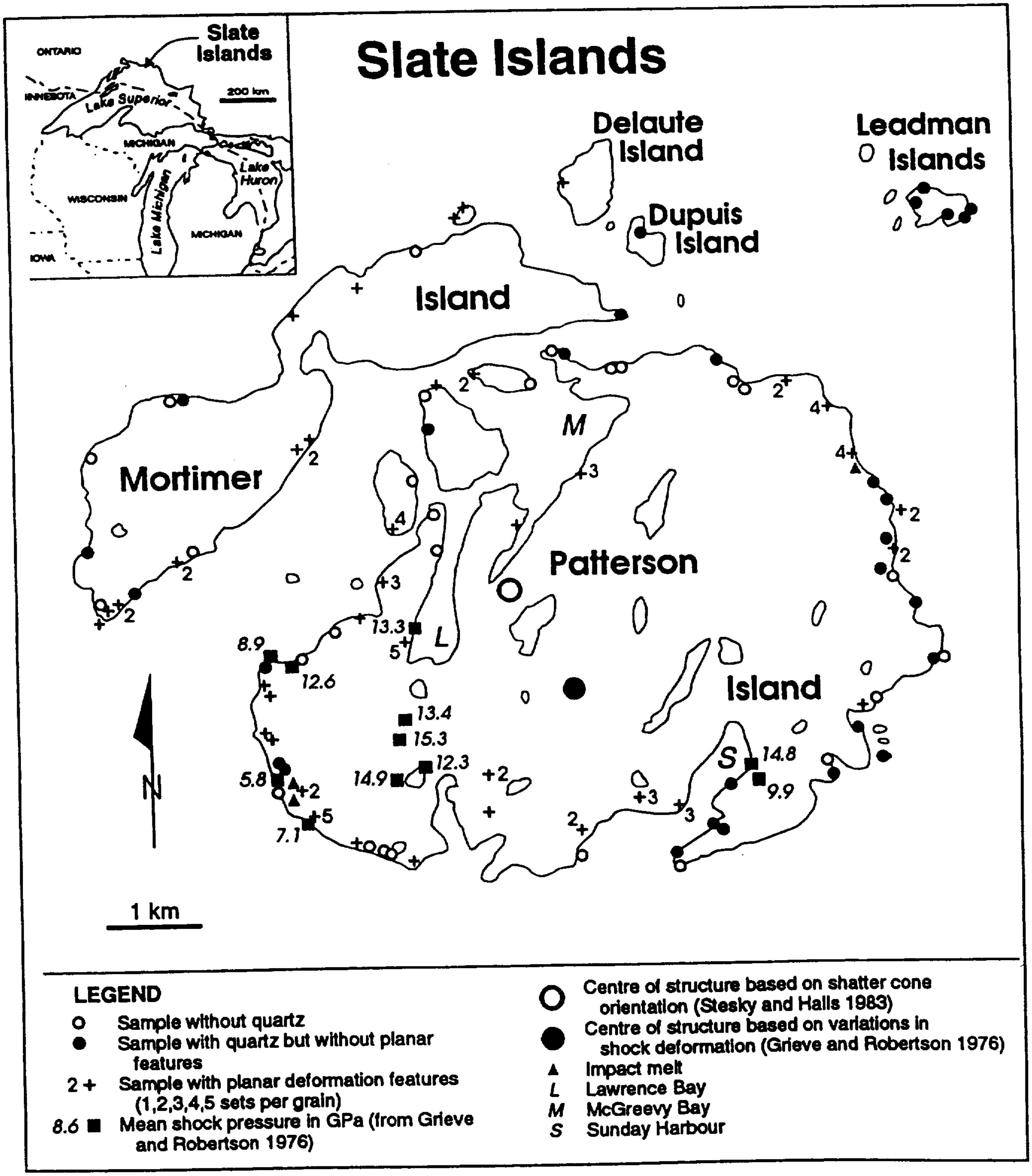

Figure 14.1. Distribution of shock metamorphic features in quartz and of impact melts.

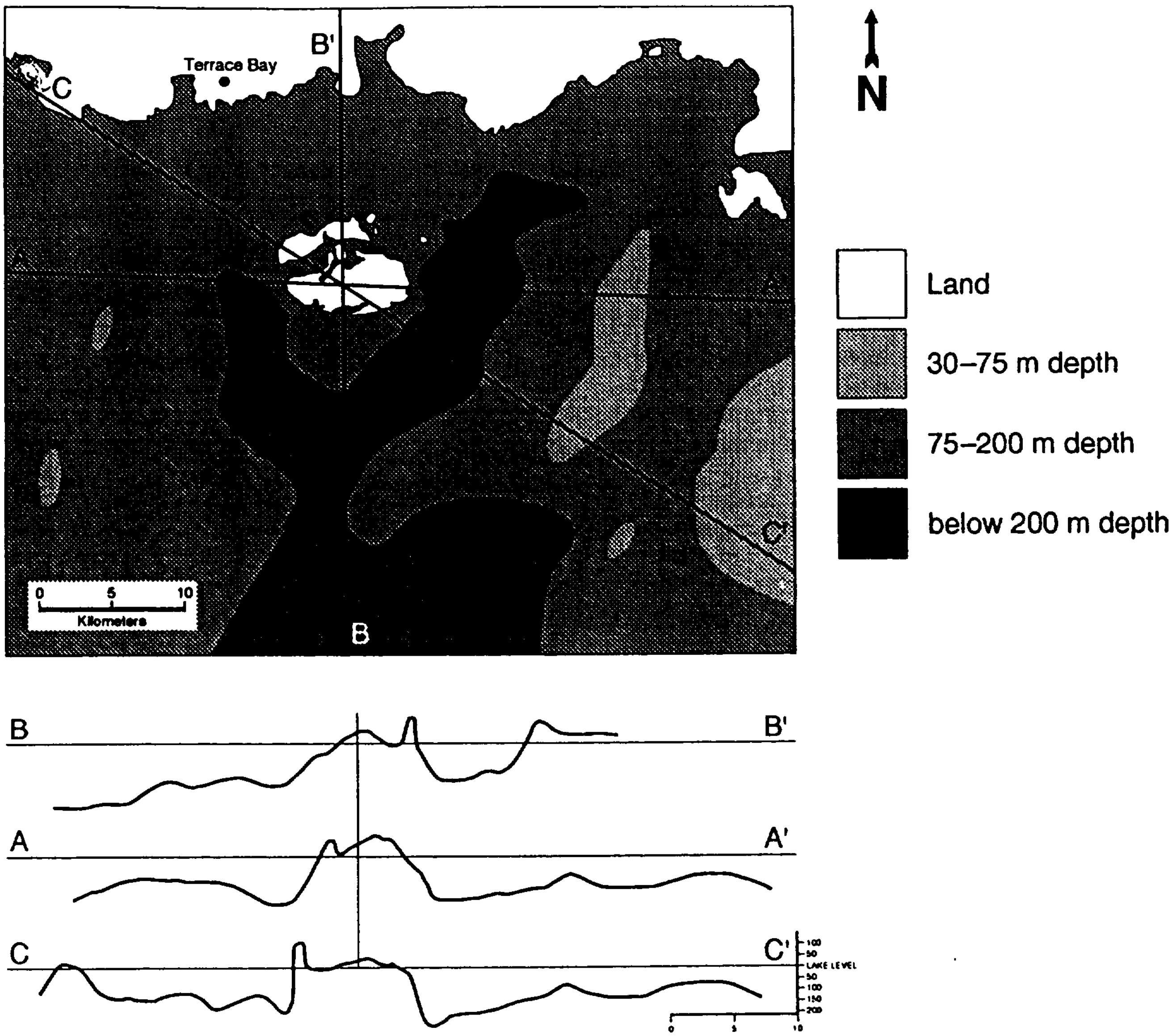

Figure 14.2. Size and shape of the Slate Islands impact structure based on Canadian national topographic and bathymetric maps.

when struck with a geologist's hammer. We believe this brittle deformation to be related to the Slate Islands impact event.

SIZE OF THE SLATE ISLANDS STRUCTURE

Halls and Grieve (1976) and Grieve and Robertson (1976) describe the Slate Islands Structure as a complex impact crater and the island group as the emergent portion of a central uplift. The island group is approximately 7 km in diameter and is surrounded by a peripheral trough and annual ring. Figure 14.2, similar to that of Halls and Grieve (1976), is based on hydrographic and topographic data. Three topographic profiles AA', BB', and CC', indicate that the structure is about 32 km in diameter. Assuming this estimate to be correct, the amount of structural uplift should roughly be 2 to 3 km, considerably more than observed. An erosion of the central peak, combined with sedimentation within and especially north of the island group near the mainland, possibly can account for the discrepancy between the observed and theoretical uplift.

A preliminary search for breccias, shock metamorphic rocks and shatter cones on the mainland north of the island group was unsuccessful. If no evidence for shock or breccias can be found on the mainland north of the islands, the above estimate of the crater diameter may be incorrect and the crater may be smaller.

IMPACT ROCKS
Shatter Cones

Shatter cones are a type of fracturing produced by the passage of a shock wave through rocks and are believed to be indicative of asteroid or comet impact. Complete cones are rarely exposed and commonly the fracture surface is only a portion of a cone characterized by linear ridges and grooves radiating from a cone apex. Parasitic parts of cones lie on the surface of larger cones (Dietz 1968). Statistically the cone axes point to a central focus, the point of impact.

Stesky and Halls (1983) have studied the distribution and orientation of shatter cones on Slate Islands. Based on their structural analysis involving some structural correction of some sites using paleomagnetic data, the inferred impact point lies at a height of about 1 km above the present land surface about 0.5 km east of the southern third of Lawrence Bay. Stesky and Halls' (1983) shatter cone study is amongst the most detailed shatter cone studies conducted anywhere.

We have documented a considerable number of shatter cone locations in addition to Stesky and Halls' (1983) and wherever possible measured the orientation of the cone axes. Shatter cones occur in practically all bedrock units but not in the impact melt rocks, which, however, contain shatter-coned inclusions, as observed at one location on the west-central shore of Patterson Island. The cones, in general, are very well developed, especially in Keweenawan metabasalts and Proterozoic metasediments. They range in size from 1 to 2 cm to several metres long and we believe that we have discovered some of the largest shatter cones, if not the largest ones, exposed anywhere on Earth. They occur in felsic metavolcanic rocks on the eastern shore of McGreevy Harbour (Photo 14.1). They are at least 10 m long and their cone axes are more or less vertical, the apexes pointing upwards. One cone surface at its exposed base is at least 7 m wide, making up perhaps 33% of a complete section perpendicular to the cone axis. Therefore the largest cone observed may have a circumference of about 20 m at its base. Horsetail-like ridges and grooves and small, parasitic cones occur all along the exposed surfaces of the "megacones".

Photo 14.1. Approximately 10 m long shatter cone in felsic metavolcanic rocks, McGreevy Bay, Patterson Island.

Breccias

A variety of impact breccias occur on the islands. Amongst them are monomict breccias common on Delaute and Mortimer islands and clastic matrix breccias of various colours and breccias that have an aphanitic clastic or a melt matrix. The monomict breccias are probably the result of in-situ brecciation. The clastic matrix breccias form dikes from about 1 cm to a few metres wide. We also have noted large outcrops of breccias, up to about 20 m long and 15 m high, where contacts with bedrocks are not exposed. Breccias can be observed in most outcrops along the shorelines of practically all islands of the Slate Islands group of islands and occur also on the islands themselves where, however, they are rarely well exposed. It is therefore not unreasonable to assume that all the bedrock of the islands are cut by breccias and may constitute a parautochthonous megabreccia. Some clasts of this megabreccia may be several hundred metres in size.

At a number of occurrences, altered glass fragments, up to about 5 cm in diameter have been noticed during our field and preliminary microscopic investigations. The breccias are undeformed, .that is, they lack any evidence of post-impact deformation. Clasts within them may be shatter coned.

Glass-Free Clastic Matrix Breccias

Breccias that macroscopically do not exhibit any altered glass fragments are most common amongst the Slate Islands breccias. They form anastomosing networks of dikes and irregularly shaped bodies. They appear to derive their colour from their clasts and minor post-impact alteration. Along the west coast of Patterson Island, breccias in general are brick-red reflecting the abundance of hematite-rich clasts of Gunflint Formation ironstones. Along the east coast of this island, breccia bodies in general are green or greenish grey. This is not a new observation and has also been reported by Sage (1991).

Clasts in the breccias range from submicroscopic to over 10 m and possibly much larger if our assumption that the bedrock constitutes a megabreccia, is correct. Small clasts are commonly angular, large ones are angular to subrounded. Shatter coned fragments have been observed and in our preliminary microscopic investigations we observed shock metamorphic features in quartz and plagioclase indicative of shock pressures of over 10 GPa. Clasts commonly reflect the nearby host rocks but exotic fragments of rocks not found in outcrop nearby, or not at all on the island group, also occur. We have, for example, observed sandstone and siltstone clasts in a breccia on Dupuis Island that strongly resemble sedimentary rocks of the Jacobsville Formation.

An occurrence of a glass-free clastic matrix breccia found in Sunday Harbour of southern Patterson Island may be correlative with Bunte Breccia deposits of the Ries impact crater of Germany. Bunte Breccia (Hüttner 1969; Engelhardt 1990) at the type location occurs in the megablock zone and around the crater up to a distance of 40 km from the centre of the Ries crater. Bunte Breccia deposits in the Ries crater are up to 100 m thick. Fragments are mainly derived from the upper target rock stratigraphy, namely sedimentary rocks. Granites and gneissic basement rock components are less abundant. Secondary cratering caused by the ejection of large blocks led to a significant intermixing with local, little consolidated rocks outside the crater. Fragments in the Bunte Breccia do not exhibit significant microscopic shock metamorphic features. However, planar features in quartz have been observed in quartz of basement rock clasts (Graup 1978) as have shatter cones in limestone and granite (Dressler et al. 1969; Engelhardt 1990). Glass, either as bombs or small fragments, is absent. Suevite overlies the Bunte Breccia. The contact between the two units, where observed, is sharp.

Several outcrops of breccia close to a suevite occurrence at Sunday Harbour are tentatively interpreted here as Bunte Breccia. Strongly fractured blocks making up the breccia are possibly up to 10 m in size and consist of grey, shatter-coned siltstone and brown and red siltstone and sandstone. The brownish-red rocks may represent Jacobsville Formation. The gray siltstones and the reddish units have not been observed by us anywhere on the island group—with the exception of some clasts of Jacobsville rocks in a breccia at Dupuis Island (see above)—and may represent upper target rock stratigraphy. No glass or altered glass fragments have been observed in this breccia. Both the nearby outcrop of suevite and the Bunte Breccia occur at lake level and no contact between the 2 rock units has been observed. There is also no exposure of the bedrock on which the breccia is deposited.

Glass-Bearing Clastic Matrix Breccia (Suevite)

Clastic matrix breccias that contain macroscopically identifiable altered glass fragments occur in several places on the shores of Patterson Island and on Dupuis Island. Their mode of occurrence is similar to that of the glass-free breccias, that is, they form anastomosing networks and dikes and some or all of the "glass-free" breccias may in fact contain microscopic glass fragments. At Sunday Harbour is an outcrop of glass-bearing breccias that may not represent an intrusive body but a "crater suevite" or "fall-out" suevite (see below).

Clasts in the glass-bearing breccias are commonly shock metamorphosed and breccias characterized as glass bearing and containing shock metamorphosed rocks are termed "suevite". At the type location of the Nördlinger Ries in Germany (Engelhardt 1990 and references therein), suevite is an unsorted and unbedded, polymict breccia consisting of target rock fragments and glass set in a fine-grained groundmass of mineral, rock and glass fragments. Rock and mineral clasts exhibit all stages of shock metamorphism. Glass is commonly recrystallized and altered — only narrow upper and lower chilled zones of the Ries suevite deposits contain unaltered glass — and is believed to have formed through shock induced melting.

Two types of suevite have been distinguished in the Ries; a fall-out suevite and a crater suevite. In the fall-out suevite, glass forms aerodynamically shaped bombs and "fladen", that is, pancake-shaped bodies commonly with overturned rims. Bomb and fladen do not occur in the crater suevite indicating that the crater suevite never left the crater cavity during the impact process. Suevite dikes have been observed in the scientific drill hole Nördlingen 1 in basement rocks underlying the crater suevite (Bayerisches Geologisches Landesamt 1977). At the Ries crater, fall-out suevite contains 30 to 50% glass in the groundmass, the groundmass making up about 80 vol.% of the breccia. Fragments of sedimentary rocks are scarce. In the crater suevite, studied in only 2 drill holes, glass is altered and volumetrically makes up considerably less than in the fall-out variety.

On Slate Islands, suevite dikes have not been studied in great detail yet. They contain rock clasts derived from host rocks and rock units not exposed nearby. It is very difficult to identify glass fragments with the naked eye or a hand lens. Most identified glass fragments were only 1 to 2 cm in size or smaller and greenish-grey and vesicular. All glass appears to be altered.

The suevite exposure near the breccia outcrops interpreted as Bunte Breccia in Sunday Harbour, has a preserved thickness of approximately 8 to 10 m. The rock is unsorted, friable and does not exhibit any bedding. Grey fluidal, altered glass fragments are up to 5 cm in size. They are not shaped aerodynamically. Target rock fragments, mainly siltstones, quartz-feldspar porphyries, up to about 1 m or more in size are common. Quartz, occurring as small mineral fragments in the suevite matrix or in rock fragments, exhibit unequivocal shock metamorphic features, namely planar features. Up to 5 sets per grain have been observed. Feldspar is commonly strongly saussuritized and does not show planar features. A few grains are recrystallized, the recrystallization possibly being after maskelynite. Shock metamorphic quartz grains are commonly strongly hematite stained. Upon recrystallization the brownish stain is lost. The recrystallization commences at the borders of individual quartz grains, commonly leaving a brownish, non-recrystallized core.

Fluidal, in places vesicular brownish glass shards make up about 1 to 3% of the rock. This relative low glass content and the lack of aerodynamically shaped glass bodies are characteristics of crater suevites. Fall-out suevite may be present on the islands farther away from the impact centre or definitely in Lake Superior in the area surrounding the Slate Islands group of islands. Based on preliminary microprobe analyses the alteration product of the glass fragments in the main mass of the Sunday Harbour suevite is an illite. Vesicular quartz glass fragments (lechatelierite) are also present.

Beneath the main mass of the Sunday Harbour suevite is a rock unit originally interpreted as impact melt breccia (Dressler et al. 1994) because of its fine-grained basaltic appearance and because of the shape of some feldspar porphyry inclusions suggesting incipient melting. Microscopic investigations and the 1995 field investigations, however, led us to a reinterpretation of the basaltic looking rock. It is a finer-grained suevite variety, the matrix of which is packed with tiny mineral, rock and altered glass fragments. The glass of this finer-grained, dark grey suevite is altered to chlorite as determined by microprobe. Clasts in this suevite are also shock metamorphic. Quartz exhibits up to 5 sets of planar deformation features.

Impact Melt

Two varieties of impact melt rocks occur on the shoreline of Patterson Island. One of them is an inclusion-rich, aphanitic, glassy looking, brick red melt breccia occurring on the western shore of the island. It is commonly densely packed with inclusions of target rocks, predominantly Gunflint Formation ironstones and diabase. The matrix is in places vesicular and commonly fractures conchoidally. We have not studied this melt breccia in any great detail yet, however, petrographic, geochemical and geochronological investigations will be conducted in the near future.

The other impact melt variety is grey and fine grained and has been observed at 2 locations on the western and 1 location on the eastern shore of Patterson Island. One of the occurrences has been described by Sage (1991) as an intrusive diabase breccia and according to Sage (1991) by Halls as a conglomerate incorporated into a flow top. Our interpretation of the rocks as impact melts is based on field and petrographic observations.

At the location described by Sage (1991) the rock intrudes Keweenawan metabasalts and diabase but may be subaerial in part of the outcrop. The contact relationships with nearby rocks at the other occurrence on western Patterson Island are also not clear and the rock may be intrusive or subaerial. On the eastern shore of the island, however, the melt forms a layer within a glass-free clastic matrix breccia or suevite deposit.

The melt rocks on western Patterson Island contain inclusions (up to 3 m in diameter) of cherty ironstone and diabase (Photo 14.2), some of which are plagioclase-rich and resemble fine-grained anorthosite. A shatter-coned clast has been observed in the breccia. On the eastern shore, inclusions (up to about 5 cm in size) are mafic metavolcanic rocks, feldspar porphyry, granite, ironstone, Keweenawan metabasalt and diabase.

Under the microscope the grey, fine-grained impact melt contains inclusions of which the smallest ones are only a fraction of a millimetre in size. It consists of lath-shaped and long needles of plagioclase,

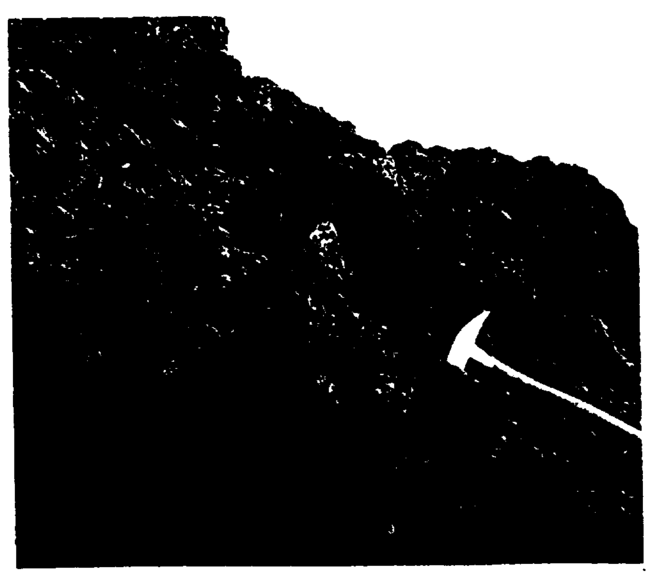

Photo 14.2. Impact melt with clasts of chert, Keweenawan metabasalt, and diabase. West shore of Patterson Island.

long and stubby biotite, which is possibly pseudomorphic after pyroxene, and a devitrified, dendritic mesostasis. Some plagioclase laths have cores filled with devitrified glass—in microscopic appearance similar to the mesostasis—biotite or opaque minerals, or a combination of 2 or 3 of these components (Photo 14.3). The shape of the biotite/pyroxene, the plagioclase and opaque minerals (Photo 14.4) are suggestive of rapid mineral growth and cooling of the rock. Minute relicts of light greenish pyroxene in biotite with slender, dendritic cores are also suggestive of rapid, skeletal growth. The devitrified mesostasis consists of fan-shaped plagioclase or sanidine with, in places, elongate iron oxide needles parallel to the plagioclase or sanidine needles.

Photo 14.3. Skeletal plagioclase laths filled with mesostasis. Impact melt. West shore of Patterson Island. Plane polarized light. Length of photograph is 0.75 mm.

Various clasts occur in the melt. Amongst them are quartz (Photo 14.5), recrystallized chert, an anorthositic rock, not known amongst the target rocks on the islands, and carbonate. Scarce relicts of planar deformation features were recognized in one quartz clast. These shock features have been largely obliterated by thermal recrystallization. Most clasts are in chemical disequilibrium with the melt as indicated by clast specific reaction coronas, similar in part to those described from other terrestrial impact structures such as Mistastin (Grieve 1975) and Manicouagan (Floran et al. 1978; Simonds et al. 1978). However, there are some distinct differences. In the Manicouagan melt, successive coronas of stubby, prismatic augite and quartz plus sanidine, apatite and smectite surround quartz clasts. In the Slate Islands melt, a corona of stubby biotite and recrystallized mesostasis separates quartz from the melt. In places the coronas are biotite poor. There is no obvious reaction rim around the anorthositic clasts, possibly because the composition of the melt (plagioclase An 57) is not very different from that of the anorthositic rock (plagioclase An 61). However, the plagioclase grains of the anorthositic rock show sieve textures similar to those in the Manicouagan melt and features between clast plagioclase grains that are, as the sieve textures, suggestive of incipient melting. The holes in the sieve in the plagioclase are filled with either sanidine or plagioclase, biotite or iron oxide. Similar observations were made by Floran et al. (1978) on plagioclase inclusions in the lower unit of the Manicouagan impact melt sheet. Only one clast of a carbonate rock was observed in the melt. It has outlines suggestive of resorption and is surrounded by a corona of biotite.

Photo 14.4. Skeletal opaque mineral, probably magnetite. Impact melt. West shore of Patterson Island. Plane polarized light. Length of photograph 0.75 mm.

SHOCK METAMORPHISM

The term shock metamorphism describes all the changes in minerals and rocks which result from the passage of high shock pressure waves. The passage of shock

Photo 14.5. Inclusion of quartz with a corona of stubby biotite. Outline of inclusion is suggestive of resorption. Impact melt. West shore of Patterson Island. Plane polarized light. Length of photograph is 3.6 mm.

waves through rocks causes permanent structural damage to minerals and rocks. The study of these shock effects is a relatively recent part of geoscience, approximately 30 years old, but much has been written on them. Specific effects are routinely used to estimate shock pressures and in 1976 Grieve and Robertson published a paper on the variations in shock deformation at the Slate Islands impact structure. Shock pressure estimates in this study are based on the relative frequency of planar deformation features of some specific crystallographic orientations in quartz. Experimental data were used to compare their observations with and to estimate the shock pressures (5.8 to 15.3 GPa) recorded in samples of basement rocks collected on Patterson Islands.

The most commonly studied shock features are those in quartz. Quartz is resistant to alteration and commonly preserves features such as PDFs (planar deformation features) very well (Dressler et al. 1994, Figure 14.1). Besides PDFs in quartz we have observed other shock metamorphic features. Amongst them are kink band in micas, PDFs in feldspars and carbonate, and shock melting of minerals and rocks. In Figure 14.1 we show some of our preliminary results of a study of the shock zoning. It is based on the examination of approximately 120 rock thin sections (courtesy of R. Sage, geologist, Ontario Geological Survey, Sudbury). We plan to refine our data over the next few months, especially by adding observation points to the interior of Patterson Island and by using the quartz shock pressure barometry in all parts of the island group. Figure 14.2 also shows some of the results of Grieve and Robertson (1976).

CONCLUSIONS AND PLANS FOR FUTURE INVESTIGATIONS

Our 1994 and 1995 field and laboratory investigations provide further evidence for an impact origin for the Slate Islands structure. The discovery of impact melt bodies will probably allow us to radiometrically age-date the structure and possibly—through detailed trace element studies—will also permit identification of the projectile type. We plan a refined study of the distribution and possibly the orientation of shock metamorphic features. Our preliminary results on the distribution of shock metamorphic features and breccias on all the islands and the common occurrence of monomict breccias on Mortimer and Delaute islands may be suggestive of a somewhat smaller size of the structure. These 2 islands may form part of a ring of uplifted basement rocks marking the inner boundary of a moat or "megablock zone" as know to exist in other terrestrial crater such as the Ries (Engelhardt 1990 and references therein).

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