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13. Project Unit 94-46. Clastic Breccias at the Slate Islands Complex Impact Structure, Northern Lake Superior

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INTRODUCTION

The Slate Islands archipelago, about 10 km south of Terrace Bay in northern Lake Superior (Figure 13.1), is approximately 7 km in diameter and most of it represents the partially eroded central uplift of a complex impact crater. On the basis of bathymetric data in the area, the structure is about 30 to 32 km in diameter (Halls and Grieve 1976, Dressler et al. 1995, Sharpton et al. 1996). Evidence for an origin by asteroid or comet impact is provided by abundant shatter cones, various polymictic and monomictic breccias in the Archean and Proterozoic target rocks, by allogenic glass-free and glass-bearing breccias, by inclusion-rich melt breccias, and by microscopic shock metamorphic features in breccia components and target rocks. Allogenic breccias are breccias formed elsewhere and transported to their present location. Acceptance of the impact origin of the structure, however, is not universal. According to Sage (1978, 1991), shock metamorphic features and target rock brecciation are the result of diatreme activity.

Asteroid and comet impacts played a major role in the formation of the planets of our solar system and in the evolution of life on Earth. The investigation of terrestrial impact structures, however, not only enhances our understanding of impact processes and associated environmental effects. Impact structures are also of important economic significance. Several major mineral occurrences, such as the nickel-copper deposits of the Sudbury structure and the uranium occurrences of the Carswell structure of Saskatchewan, gold and uranium at the Vredefort structure (South Africa) and major oil producing fields (Ames structure, Oklahoma; Marquez structure, Texas) are associated with impact (Reimold and Dressler 1990; Grieve and Masaitis 1994). The investigation of impact processes, therefore, is not an esoteric field of geology, but a significant part of planetology and geoscience.

Erosion on Slate Islands and large wave-battered shore exposures provide exceptional two- and three-dimensional views of lithological and structural elements of the central uplift of a complex impact crater. To our knowledge, there is no other terrestrial impact structure of comparable size with equal or better exposures of rock units and deformational features of the central crater region. It is

because of these reasons that we selected Slates Islands for a detailed and multi-year geoscience study. This summary report represents the third year of a co-operative study by the Field Services Section (Northwest) of the Ontario Geological Survey and the Lunar and Planetary Institute, Houston, Texas.

The general geology of the Slate Islands archipelago has been described by Sage (1991) and a short summary based on Sage's work is given in Dressler et al. (1995). The reader is referred to these publications for information on the bedrock geology of the island group. Early studies on the Slate Islands impact structure include: Halls and Grieve (1976), Grieve and Robertson (1976) and Stesky and Halls (1983).

In this report, we provide a summary of the impact process as presently understood. We also present some of the results of our laboratory investigations conducted in 1995 and 1996. We describe in some detail the various clastic breccias encountered on the islands during our 1994 and 1995 field work and relate them to the various phases of the impact process. A more encompassing treatise on the breccias has been submitted for publication. (Dressler and Sharpton 1996).

THE IMPACT PROCESS

About 150 impact craters are known on Earth (Grieve et al. 1995) and each year several structures are added to this number. Three types of impact craters are known; "simple craters", "complex craters" and "multi-ring basins". Simple craters are bowl-shaped. In sedimentary targets they are up to about 2 km in diameter, in crystalline rocks up to about 4 km. Complex craters are larger and are characterized by a central uplifted peak or peak ring surrounded by an annular trough. Figure 13.2 shows, in a simplified form, the formation of a complex impact structure. The last profile in this figure represents a section across the Slate Islands impact structure. The largest impact structures are multi-ring structures. They are characterized by structural rings around a topographic crater. They are best known from the Earth's moon. On the basis of their sizes, there are three multi-ring structures on Earth; the Vredefort structure in South Africa, the Chicxulub structure in Mexico (Yucatan) and the Sudbury structure.

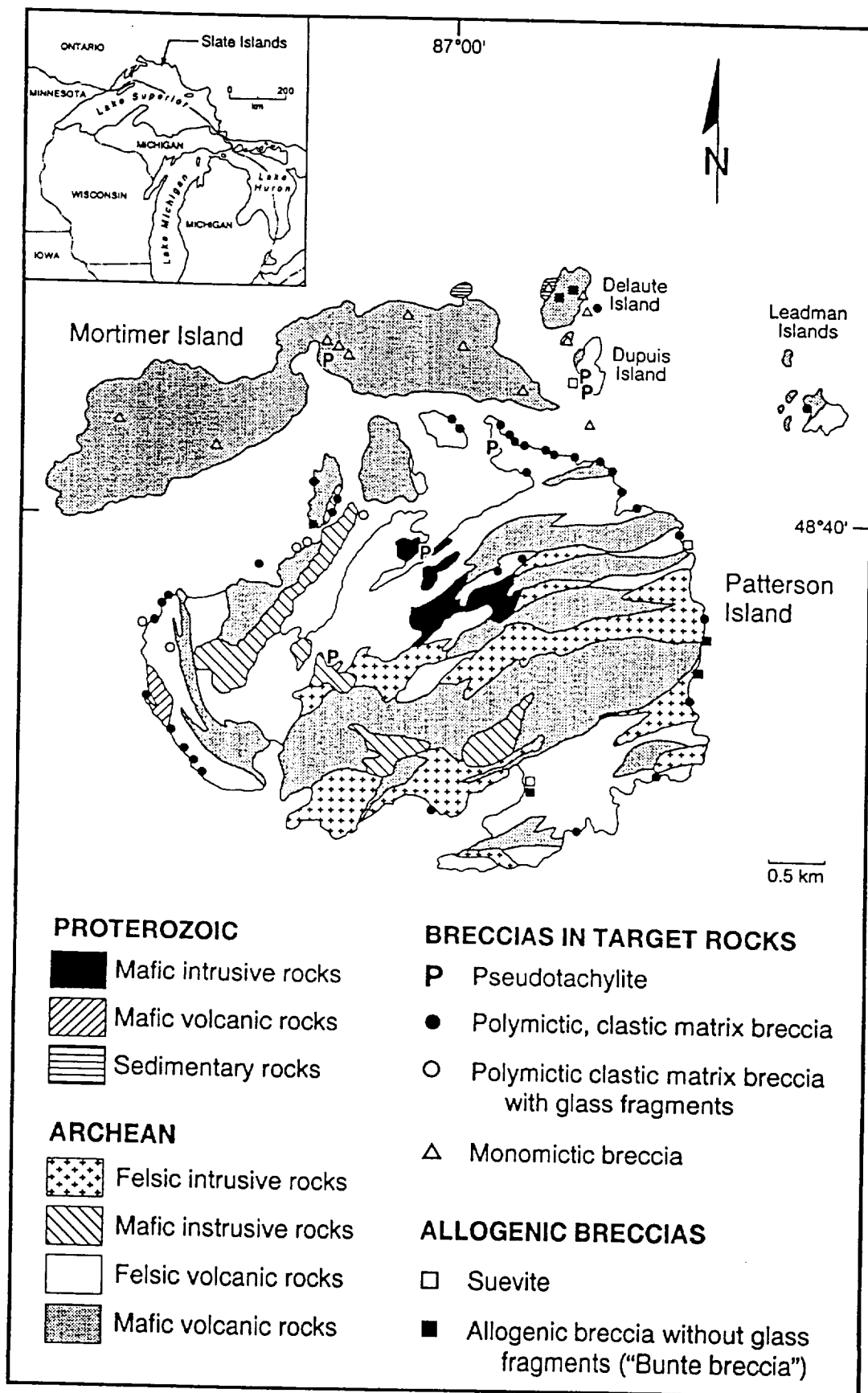


Figure 13.1. The Slate Islands impact structure, general geology and location of breccia types observed. (After Dressler and Sharpton 1996).

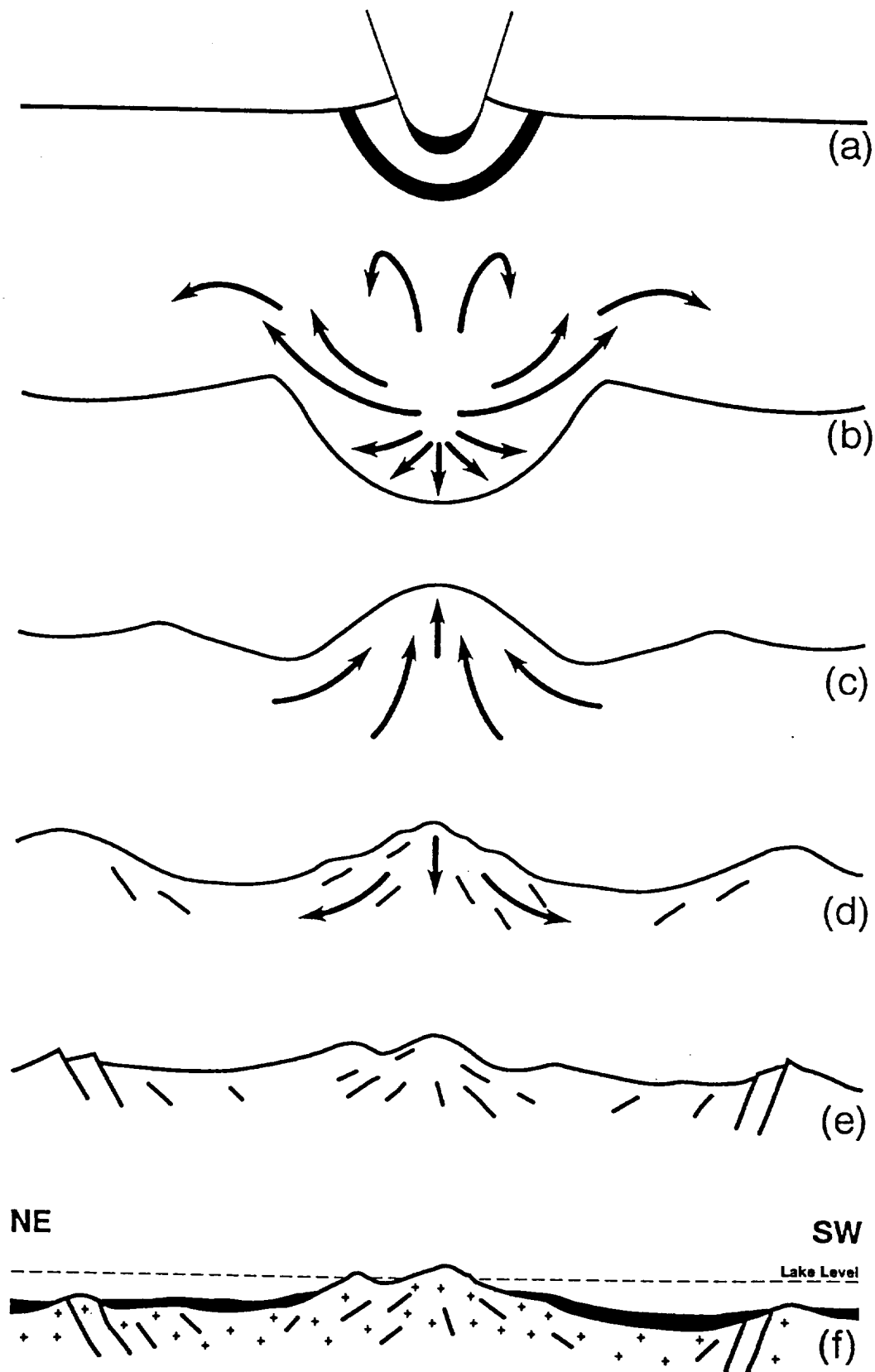


Figure 13.2. Formation of a complex impact structure. a) Impact and evaporation of projectile - growing transient crater lined with impact melt. b) Compression and excavation — growth of transient crater. c) Central uplift and continuing excavation; d) Collapse of central uplift and crater modification; e) Final form of complex crater; f) Present shape of Slate Islands impact structure (black: allogenic breccias and impact melt, assumed).

Upon impact (see Figure 13.2), a system of shock waves sets target rocks into motion hemispherically downward and outward while, near the target surface, rocks are ejected from the growing excavation cavity, leading to the formation of a "transient crater". For larger craters, greater than approximately 2 to 4 km in diameter, this transient cavity is unstable and collapses immediately to form a larger final crater with complex morphology. This late-stage modification is characterized by rebound of the crater basement in the crater centre, and inward collapse and broadening of the original crater walls. Throughout this complex process of initial compression, excavation, uplift, and broadening, breccias are formed in the target rocks. Ejected material is either deposited outside and around the crater form or falls back into the crater cavity. Target rocks and breccia components experience various degrees of shock metamorphism. At the Slate Islands we have observed a wide range of microscopic shock features, ranging from non-diagnostic, simple kink bands to impact-diagnostic planar deformation features in feldspar and quartz (Photo 13.1) and mineral and rock melting. Below we describe the various impact breccias and try to relate them to various phases of the impact process, namely compression, decompression during central uplift and central uplift collapse/excavation, and crater modification.

SLATE ISLANDS IMPACT

Breccias observed at the Slate Islands impact structure resemble those known from a good number of other terrestrial impact structures. Pseudotachylite, polymictic clastic matrix breccias and monomictic breccias are found within the target rocks. Suevite and glass-free, allogenic breccias represent fall-out and fall-back breccias. Slate Islands breccias commonly contain mineral and rock fragments exhibiting shock metamorphic features such as planar deformation structures in quartz and feldspar and vitrified rock and mineral fragments.

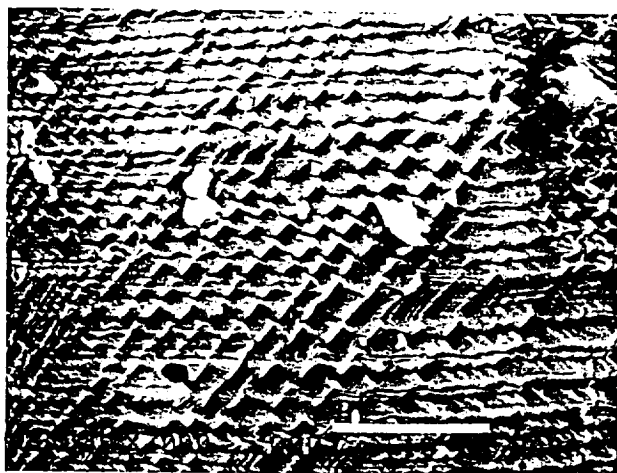


Photo 13.1. Planar deformation features in quartz. Vein quartz clast in suevite. SEM image. Scale is 10 μ m.

Breccias in Target Rocks

The degree to which the target rocks of the Slate Islands impact structure are brecciated varies from place to place. However, we believe that macroscopically recognizable breccias, consisting of amalgamated clasts less than a few metres across, make up 15 to 25% of the bedrock of the archipelago.

Pseudotachylites are formed by tectonic processes and are found also in impact structures. During tectonism they form through friction melting (Magloughlin and Spray 1992; Swanson 1992; Spray 1995) or by strong cataclasis (Wenk 1978). In impact structures, they are generated by friction melting and/or shock brecciation and/or by impact melting (Reimold 1995 and references therein). Pseudotachylite formation is a very rapid process, probably ranging in the microsecond to a few second range.

Slate Islands pseudotachylites are compatible with the Type A pseudotachylites of Martini (1991). They form thin dikelets and anastomosing veins of extremely fine-grained melt rock or devitrified glass with few country rock and mineral inclusions. Contacts with their host rocks are sharp. They have been observed only in relatively few places on the islands. Because of their small size, they are difficult to detect, but are believed to be fairly common. Type B pseudotachylites (Martini 1991) form large bodies and dikes in a number of impact craters such as the Sudbury and Vredefort structures but appear to be absent from the Slate Islands. They also have distinct contacts with their host rocks. Their matrices are very fine grained and clastic and commonly contain a wide range of clasts derived from nearby country rock. Both pseudotachylite types are formed *in situ*. We have observed pseudotachylite clasts in Slate Islands pseudotachylite and, in the Sudbury Structure, melt matrix pseudotachylite veinlets cutting across melt matrix pseudotachylite veins.

Polymictic, clastic matrix breccias are the most common breccias on Slate Islands, especially on Patterson Island. They contain a wide range of target rock clasts (Photo 13.2) that are angular to rounded and range in size from less than a millimetre to several metres. The breccias are



Photo 13.2. Polymictic clastic matrix breccia. Southwestern Patterson Island.

not pseudotachylite Type B breccias as their matrices are considerably coarser grained and their larger clasts are commonly more densely packed than in Type B pseudotachylites. The breccias form dike-like bodies a few centimetres to several metres thick and irregularly shaped bodies. They cut across pseudotachylite veins and contain inclusions of pseudotachylite fragments (Photo 13.3). In places, polymictic, clastic matrix breccias intrude along pseudotachylite veins, rip them apart and incorporate pseudotachylite fragments within them. The process leading to the formation of the polymictic breccias is complex. Up to seven target rock clast types have been observed in one breccia occurrence and compound breccia clasts (breccia-in-breccia clasts) have been noted.

Monomictic, autochthonous breccias have been observed mainly on Mortimer Island and several of the smaller, peripheral islands of the archipelago. They have angular, somewhat rotated fragments that are densely packed, with little clastic matrix between them. Contacts with host rocks are gradational. Outcrops of these breccias greater than 10 m in size have been observed. At one location a polymictic, clastic matrix breccia dike was noted enclosed in the monomictic breccia. It has been affected by a second brecciation event responsible for the formation of the enclosing breccia. The alignment of the dike clasts within the monomictic breccia, however, is still indicative of the original trend of the polymictic, clastic breccia dike.

Allogenic Breccia

Two allogenic breccia types (breccias formed elsewhere) appear to be present on the Slate Islands archipelago. One of them contains strongly altered glass fragments, the other is devoid of glass. By general analogy with other impact structures such as the Ries impact structure in Germany (Engelhardt 1990 and references therein), we call the first type "suevite", the second type "bunte Breccia".

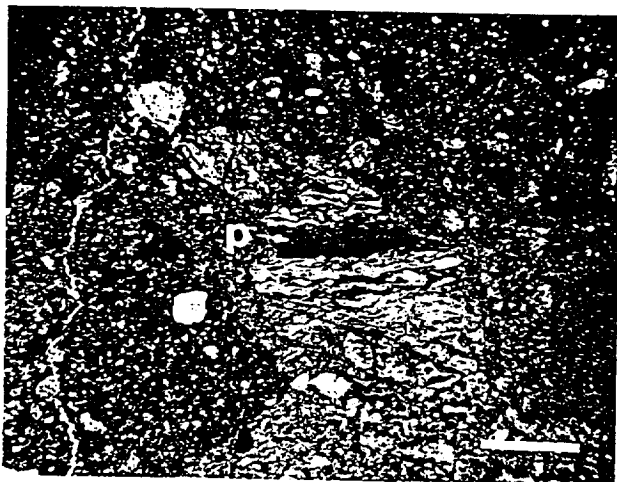


Photo 13.3. Rock clast with pseudotachylite veinlet (p) in polymictic clastic matrix breccia. Plane light. Scale 1 mm.

Suevite at the Ries crater is a polymictic, clastic matrix breccia containing glass fragments and rock and mineral clasts that exhibit features diagnostic of various degrees of shock deformation. In the "crater suevite", glass fragments do not have aerodynamic shapes while those of the fall-out suevite do (Engelhardt and Graup 1984). Slate Islands suevite occurrences are not common (see Figure 13.1) and nowhere did we note aerodynamically shaped glass fragments. Glass is altered to chlorite or smectite and many rock and mineral fragments exhibit features diagnostic of strong shock. We have observed shock metamorphic features in rock fragments indicative of peak shock pressures of up to about 15-20 GPa (Stöffler and Langenhorst 1994). Target rock clasts are derived from both Archean and Proterozoic target rock units.

Bunte breccia deposits, like the suevite deposits, are not common on the archipelago. Clasts in these deposits are mainly derived from Proterozoic target rock units, glass fragments are absent as are features diagnostic of strong shock. Shatter-coned fragments, however, do occur. Fragments range from a few millimetres to greater than 5 m in size. Fragment shapes are angular to subrounded.

DISCUSSION

Shock metamorphic features in components of the various breccias encountered on the Slate Islands archipelago and the presence of altered glass in the breccias strongly suggest that the breccias were formed by comet or asteroid impact. The impact process is a rapid process but not instantaneous. Shock waves and rarefaction affect the various target rock units across an impact structure at slightly different times. We made a number of diagnostic field and laboratory observations that allow us to relate the various Slate Islands breccias to the planetary impact process as presently understood. Our interpretations are described below.

Compression Stage

Upon impact, the initial, compressional shock waves forces target rocks into motion, downward and outward, leading to the formation of a transient crater and to *in situ* brecciation, the formation of shatter cones and microscopic shock metamorphic features and to shock melting of target rocks. No mixing of target rock fragments over long distances can occur during the compressional stage. We believe that only pseudotachylite Type A breccias form in the compressional stage. Substantial resistance had to be overcome to allow frictional melting and injection of impact melts formed *in situ*. The melts are emplaced mainly along pre-existing weaknesses in the target rocks, such as lithological contacts and fractures. Cross-cutting pseudotachylite veinlets are formed when two or more pseudotachylite bodies form and spread short distances from each other. We interpret the presence of pseudotachylite clasts in pseudotachylite in a similar manner.

Pseudotachylites form more or less *in situ*. Therefore, they should have chemical compositions similar to those of the host rocks. This has been observed in other impact craters (Dressler 1984 and references therein). Geochemical work on our Slate Islands samples is under way.

Pseudotachylites form prior to the formation of polymictic clastic matrix breccias. They are cut by these clastic rocks. We have also noted pseudotachylite clasts and pseudotachylite-bearing rock fragments in the clastic breccias, and clastic matrix breccias that intruded along pseudotachylite veins. All our observations suggest that

pseudotachylites form prior to all other breccias in the target rocks during the compressional stage of the impact process. Shatter cones also form early in the impact process and prior to the formation of the polymictic clastic matrix breccias. We have observed shatter-coned clasts in these polymictic breccias.

Table 13.1. Slate Islands Impact Breccias.

Impact Phase	Compression	Excavation/Central Uplift	Modification	Readjustment
	Faulting			
		Allogenic BX		
		???	Monomictic BX	
		Polymictic Clastic Matrix BX	??	
	Pseudotachylite Type A, Shatter Cones	??		BX: Breccia
Breccia Type	Diagnostic Observations			Impact Stage
<u>Breccias in target rocks</u>				
Type A pseudotachylite	Fluidal melt texture; thin dikelets and anastomosing veins; sharp contacts with host rocks; few clasts, some with shock features. Relatively scarce, observed on Patterson and Mortimer islands.			Compression
"Cryptic breccia"	Homogeneous rock that breaks into small, angular fragments when struck with a rock hammer. Central Patterson Island only.			Compression
Polymictic, clastic matrix breccia	Wide variety of clasts of various shapes and sizes; shock metamorphic features; altered glass in places; fragments of Type A pseudotachylite in places; forms dikes and irregularly shaped bodies with sharp contacts with host rocks; cuts across Type A pseudotachylite. All islands, but mainly on Patterson Island.			Central uplift and excavation; possibly also somewhat later.
Monomictic breccia	Monomictic, angular fragments in clastic matrix; transitional contacts with host rocks; contains fragmented, polymictic, clastic matrix breccia dikes. Mortimer Island and outlying islands only. Very scarce on Patterson Island.			Crater modification
<u>Allogenic breccias</u>				
Suevite	Shock metamorphic clasts and altered glass fragments in clastic matrix. Glass fragments have no aerodynamic shapes. South and east Patterson Island and Dupuis Island only.			Excavation
"Bunte Breccia"	Polymictic, glass-free breccia. No features indicative of strong shock.			Excavation

Excavation and Central Uplift Stage

After the passage of the compressional shock wave, decompression, central uplift and central uplift collapse affect the target rocks. All these processes lead to further deformation and brecciation of the target rocks and of earlier formed breccias. Excavation and ejection of target rock fragments and melt clasts result in the formation of allo-genic breccias within the crater cavity and the surrounding area.

It is during the decompression and central uplift stage when target rocks are in a state of cohesionless dilation. At this time large clastic matrix polymictic breccia bodies are formed and mixing of clasts over considerable distances

can occur. We suggest lateral fragment movement of up to about 2 km (Dressler and Sharpton, submitted, 1996). The presence of altered glass fragments in some polymictic breccia bodies within the target rocks is an indication that also considerable downward movement of breccia components took place, possible only during the decompression and central uplift phase of the impact process.

During excavation and ejection, allogenic, glass-free (Bunte Breccia-type) polymictic breccias and impact glass-bearing (suevite) polymictic breccias are produced. At the Bunte Breccia and Suevite type location, the Ries crater in Germany, suevite overlies bunte breccia in the megablock zone of the crater and around the topographic crater form (Engelhardt 1990 and references therein). At Slate Islands, we did not observe the glass-free allogenic

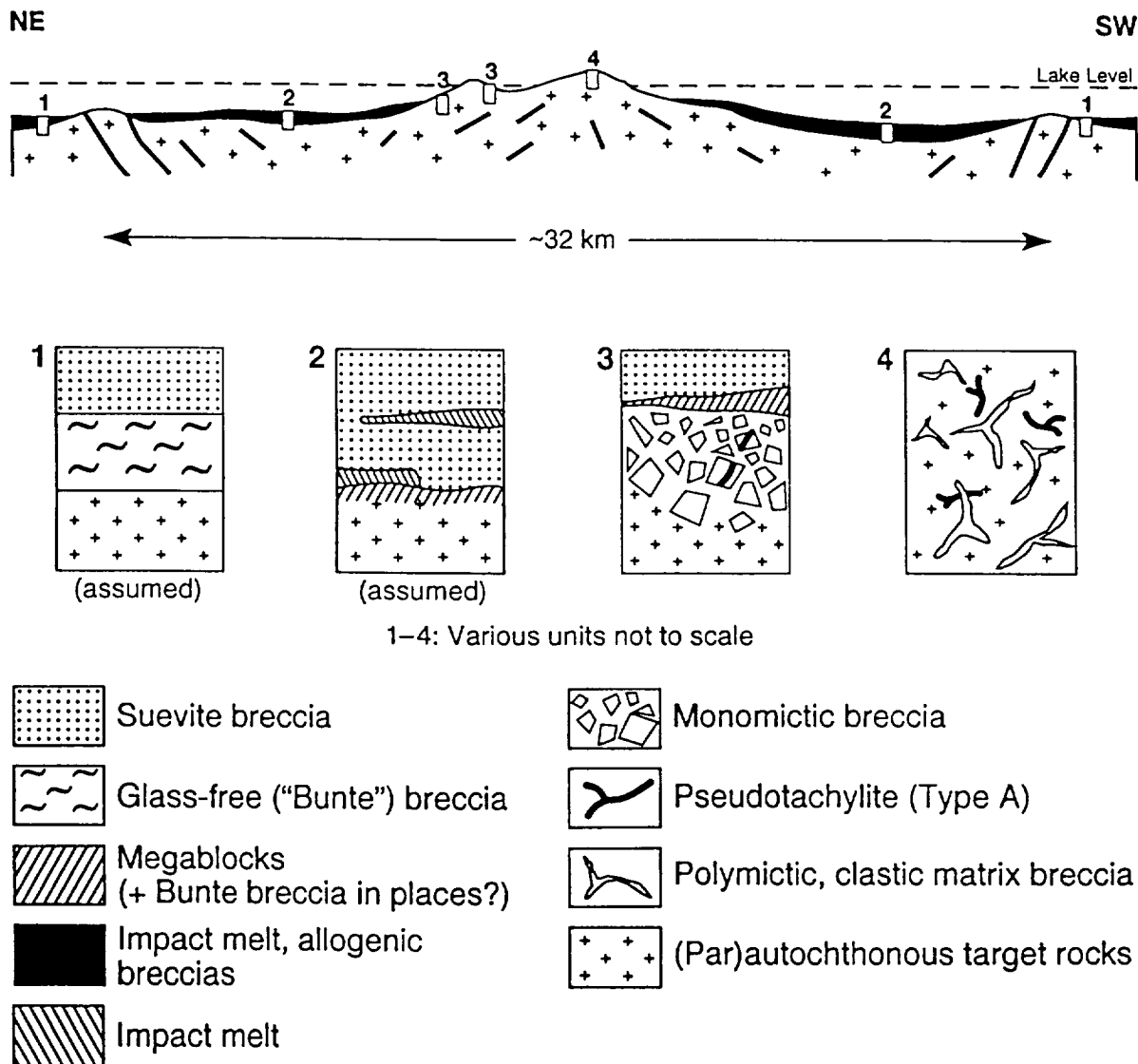


Figure 13.6. Distribution of impact breccias in section across the Slate Islands structure (after Dressler and Sharpton 1996).

breccia in contact with the suevitic breccia and we did not locate breccias on the mainland north of the archipelago. However, we believe that both allogenic breccia types occur around the island group beneath the waters of Lake Superior.

Crater Modification Stage

Following excavation, central uplift and central uplift collapse, the transient crater wall collapse results in the rotation of megablocks and the formation of fractures, faults, and breccias. Earlier formed pseudotachylite and clastic matrix polymictic breccias are affected by this, more or less autochthonous, monomictic brecciation process. At Mortimer Island, we have observed pseudotachylite that has been affected by this late, monomictic brecciation, as has a clastic matrix polymictic breccia dike at Delaute Island.

Post-Impact Processes

Weathering and hydrothermal alteration affect the breccias formed during the various stages of the impact process. This has been observed at several other terrestrial impact craters. Glass commonly devitrifies or is altered to chlorite, smectite or other alteration products. At the Slate Islands, impact glasses were transformed to smectite and/or chlorite. Tiny post-impact carbonate veinlets have also been noted by us.

CONCLUSION

In Table 13.1 (after Dressler and Sharpton 1996) we summarize our observations and interpretations. We are aware that our interpretations are based on a relatively small number of diagnostic observations. Nevertheless, we believe that the overall picture presented by us is correct. Figure 13.3 is a generalized section across the Slate Islands impact structure (after Dressler and Sharpton 1996) showing where we observed the various breccia types.

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