# 6

# Impact Melts

## 6.1. FORMATION CONDITIONS

One of the most unique features of the impact process is the virtually instantaneous melting of significant amounts of target rock, followed by the rapid distribution of this **impact melt** throughout the resulting crater to produce a variety of unusual crystalline and glassy igneous rocks. All impact-generated shock waves deposit some of their original energy as heat within the target rocks through which they pass. At relatively low shock pressures (≤40 GPa), the resulting postshock temperature rise is moderate (≤500°C), or below the melting points of most rock-forming minerals (Table 4.2). At higher pressure (~40–50 GPa), the higher temperatures produce significant melting, and at pressures (≥60 GPa) near the impact point, the shock waves deposit sufficient thermal energy to completely melt a large volume of target rock. The subsequent dynamic processes of crater formation spread this impact melt within and outside the crater as small bodies of glass in breccias and as larger bodies of crystalline igneous rock of varying size, shape, and appearance (*Dence,* 1971; *Grieve et al.,* 1977, 1991b; *Grieve and Cintala,* 1992; *Schuraytz et al.,* 1994). In large (D > 25 km) impact structures, especially those produced in crystalline igneous and metamorphic rocks, tens to hundreds of cubic kilometers of impact melt may be produced, and impact melt units can become a significant part of the geology of the structure (Fig. 6.1).

The formation of impact melts has no counterpart in other geological processes, and many details of how impact melts are formed, moved, and emplaced are still not clear. However, some general features of the process and its geological consequences have been outlined by combining theoretical models with geological studies of impact structures (*Dence,* 1971; *Dence et al.,* 1977; *Grieve,* 1978; *Grieve et al.,* 1977, 1981, 1991b; *Grieve and Cintala,* 1992; *Cintala and Grieve,* 1998). During the initial stages of an impact event at typical cosmic encounter velocities, postshock temperatures ≥2000°C are produced through a large volume of target rock close to the impact point (Fig. 3.2) (*O'Keefe and Ahrens,* 1975, 1977; *Ahrens and O'Keefe,* 1977; *Melosh,* 1989, pp. 63–64 and 122–123).

These postshock temperatures are far above the normal melting points of the target rocks and their constituent minerals. As a result, when the shock wave has passed and the pressure returns to normal, spontaneous and complete melting occurs almost instantaneously throughout a large and approximately spherical volume of target rock. The shock waves that have melted the target rock also provide kinetic energy to accelerate the newly formed melt, which immediately becomes part of the overall flow and movement of target rock that opens up the transient crater (Fig. 6.2) (*Dence,* 1971; *Grieve et al.,* 1981; *Grieve,* 1987).

A special kind of melt formation and ejection may occur during the earliest stages of contact in small regions near the interface between the projectile and the target (Fig. 3.1). In this region, extremely high shock pressures are generated, producing correspondingly high temperatures (>5000°C) in the shocked material. The resulting melted and vaporized material may then be ejected as high-velocity jets, at speeds that may exceed the original impact velocity (*Melosh,* 1989, pp. 51–53). Depending on the amount of atmospheric resistance encountered, the jets can carry material to significant distances, forming deposits of small spherules or larger glassy bodies (*Melosh and Vickery,* 1991). However, such material, which may be a mixture of vaporized projectile and target rock, is relatively minor in comparison to the large volume of melt generated subsequently within the crater.

This larger melt volume, initially located near the center of the structure, is driven downward and outward toward the floor of the developing transient crater at initial velocities of a few kilometers per second (Fig. 6.2). When the melt reaches the transient crater floor, it turns and moves upward and outward along the floor (*Grieve et al.,* 1977). At this point, the movement of the melt becomes slower and

**Fig. 6.1. Impact melt rock; cliff with columnar jointing.** Exposed erosional remnant of annular impact melt sheet at Mistastin Lake (Canada), forming a steep cliff about 80 m high. The melt unit strongly resembles exposures of normal endogenic igneous rocks and even shows two tiers of typical columnar jointing. Photograph courtesy of R. A. F. Grieve.

more complicated. The moving melt begins to incorporate cooler inclusions from the floor and wall of the transient crater. As these inclusions are assimilated, the melt cools rapidly and may subdivide into distinct units of clast-rich impact melt breccia and clast-poor impact melt (*Simonds et al.,* 1976, 1978a,b). Some of the outward-flowing melt might possibly reach the original ground surface, escape from the crater, and spread out over the area surrounding the crater rim like a lava flow before it solidifies. Such extrusive impact melt bodies may exist around a few well-preserved terrestrial impact structures (e.g., *French et al.,* 1970), but the identifications so far are uncertain and such units will not be preserved in older, deeply eroded structures.

The only impact melt definitely known to be ejected from the crater occurs in small (<50 cm) objects composed of rock and mineral clasts in a matrix of rapidly quenched glass; these melt bodies (*Fladen*) form an important component of the melt-fragment breccias (**suevites**) deposited in and around the final crater. Most of the coherent melt layer remains within the evolving crater and finally comes to rest on top of breccias that have already partially filled the crater. Geological support for this model comes from the observed concentration of melt-rich materials in the upper part of the crater-fill breccia deposits at both large and small impact structures (*Dence,* 1968; *Grieve,* 1978; *Grieve et al.,* 1977).

In small impact structures, e.g., Brent (Canada), most of the preserved impact melt occurs as small bodies in suevites and as the matrixes of clast-rich breccias. In larger structures, where more melt is produced, e.g., Clearwater Lakes (Canada) and Manicouagan (Canada), the melt may also form thick coherent bodies that extend over much of the interior of the final structure (Fig. 6.1) (*Dence,* 1971; *Grieve et al.,* 1977). In the past, these occurrences of apparently normal volcanic or intrusive igneous rocks were frequently cited as evidence for the internal origin of many structures now accepted as the results of meteorite impact. However, unlike normal igneous rocks, which originate by equilibrium melting deep within the Earth and then rise slowly to the surface as molten magma, impact melts are produced by the rapid and complete melting of near-surface target rocks directly beneath the impact site itself. This different origin leaves distinctive features in the resulting impact melts, such as shock-metamorphosed inclusions, evidence of extremely high temperatures, unusual bulk chemical compositions, or chemical signatures from the projectile itself. It is therefore possible to distinguish impact melts from normal igneous rocks.

## 6.2. IMPACT MELT VOLUMES AND CRATER SIZE

Impact melt is a significant component of the rocks produced by the cratering event, especially in large impact structures. Theoretical estimates suggest that, at typical impact velocities of 15–30 km/s, as much as 40–60% of the total kinetic energy of the impacting projectile is transferred into the target rocks as thermal energy. Even though not all this energy is effective in melting the target, the volume of impact melt produced may still be 10 to >100× the volume of the original projectile (depending mostly on the projectile's impact velocity) (*O'Keefe and Ahrens,* 1975, 1977; *Ahrens and O'Keefe,* 1977; *Melosh,* 1989, pp. 63–64 and 122–123). Additional studies (*Grieve and Cintala,* 1992) suggest that the volume of impact melt produced ($V_m$, in cubic kilometers) increases expontentially with crater diameter (D, in kilometers) and that the two quantities can be related by an equation of the form

$$V_m = cD^d$$

Application of theoretical and experimental cratering studies suggests approximate values of c = 0.0004 and D = 3.4 for the dataset used (*Grieve and Cintala,* 1992).

This relation indicates that large impact events (which form large craters) produce proportionately larger volumes of impact melt (*Dence,* 1971; *Grieve and Cintala,* 1992), but the available data (both theoretical and geological) are not precise enough for detailed estimates. Theoretical problems include significant uncertainties in various experimental parameters, as well as the difficulty of extrapolating the results of small laboratory experiments to the conditions of large impact events.

There are also several geological complications. Target rock compositions and physical properties are apparently important. Some large impact structures [e.g., Ries Crater (Germany)] contain little impact melt. This anomaly is explained (*Kieffer and Simonds,* 1980; *Grieve and Cintala,* 1992) by the observation that the target rocks in these melt-poor structures contain significant amounts of sedimentary rocks. Unlike crystalline rocks, sedimentary rocks may be both porous (e.g., sandstones) and volatile-rich (limestone, dolomites, and evaporites). Although impacts into porous rocks tend to produce proportionately more melt than impacts into denser crystalline rocks (*Kieffer,* 1971; *Kieffer and Simonds,* 1980; *Stöffler,* 1984), much of the melted material may form small vesicular aggregates that are ejected from the crater with a plume of expanding volatiles (*Kieffer and Simonds,* 1980). Crater size has another effect: Relatively more melt is ejected

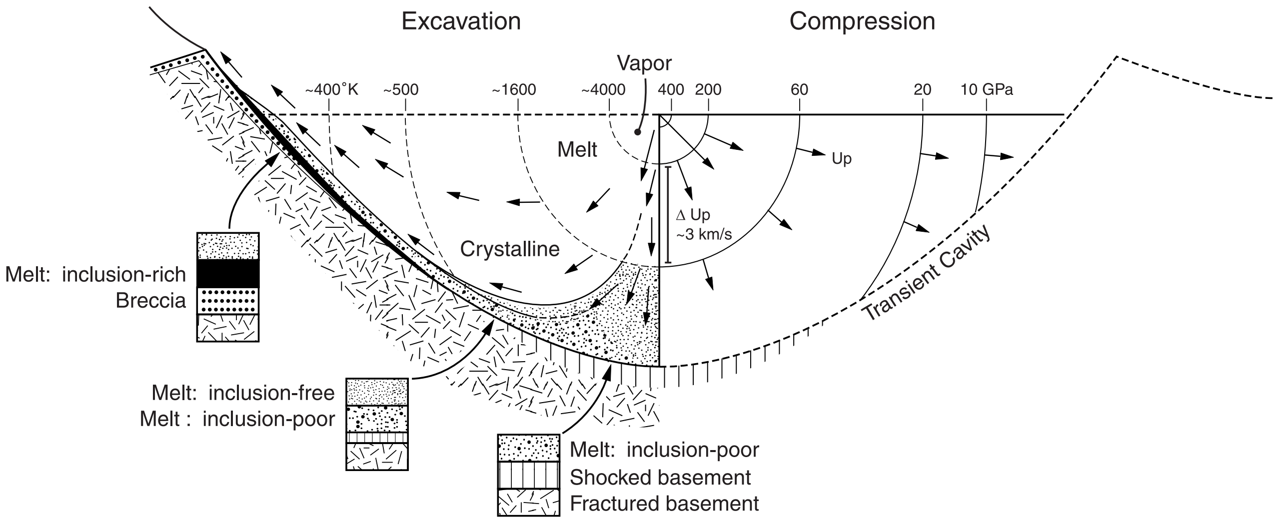

**Fig. 6.2. Impact melt; formation and movement through transient crater.** Cross-section diagram through a transient crater, showing formation and subsequent movement of impact melt. Concentric circles around the original impact point show isobars of peak shock pressures (right side, "Compression," in GPa) and isotherms of postshock temperatures (left side, "Excavation"). The small zone of pressures >200 GPa close to the impact point is briefly occupied by a mixed projectile-target vapor; the original body of impact melt forms immediately outward from this zone at pressures >60 GPa. Kinetic energy, imparted to the melt volume by shock waves, drives the originally hemispherical volume of melt downward and outward with particle velocities **($U_p$)** >1 km/s. When the melt reaches the floor of the excavation zone, it turns and flows upward along the developing transient crater floor. During this stage, the melt can incorporate xenoliths of shocked and unshocked rocks from the crater floor and walls, and it may separate into inclusion-free, inclusion-poor, and inclusion-rich varieties. Some flowing melt may even reach the ground surface and spread out beyond the crater rim. During the subsequent crater modification stage, the melt located at high levels on the floor near the rim slumps back into the crater to form disseminated small bodies and larger layers of melt toward or at the top of the crater-fill breccias. (Modified from *Grieve et al.,* 1977, Fig. 5.)

from smaller craters than from larger ones, and the ejected melt is less apt to be preserved in geologically old structures. Additional geological uncertainties include (1) difficulties in estimating the original volume of eroded impact melts in older structures and (2) uncertainties in estimating melt volumes in poorly exposed structures or in buried structures explored only by drilling.

Because of these uncertainties, impact melt volumes measured in actual impact structures differ from the calculated values by factors of as much as 2–7×, and calculated impact melt volumes generally exceed measured ones (*Grieve and Cintala,* 1992, Fig. 3). These differences are reasonable in view of the theoretical and experimental uncertainties involved, and the model is good enough for general predictions. For instance, the model clearly shows that the volume of impact melt formed in small craters (diameter <5 km) is relatively small ($\leq 1$ km$^3$). Even so, this melt is important. It generally occurs as distinctive glass fragments in breccias deposited in and around the crater, and these fragments are often easily identified as impact products. However, because melt volume increases even more rapidly than the cube of crater diameter, impacts of larger projectiles (D = 1–10 km), which produce craters 10–200 km across, can generate 10 to >1000 km$^3$ of impact melt. Such volumes are similar to those of many units of internally generated igneous rocks, and it is not surprising that many large impact structures were originally identified as the results of major endogenic igneous events.

## 6.3. IMPACT MELT VARIETIES IN THE NEAR-CRATER ENVIRONMENT

Virtually all (>99 vol%) the melt formed in an impact event is deposited within the resulting crater or within a few crater radii beyond the rim (*Dence,* 1971; *Grieve et al.,* 1977; *Grieve and Cintala,* 1992). In these locations, the impact melt occurs in a variety of forms: (1) discrete, small (millimeter- to centimeter-sized), irregular, generally glassy objects in **suevite** crater-fill breccias or in nearby ejecta deposits around the crater; (2) glassy or crystalline matrices of clast-bearing allogenic breccias (**impact melt breccias**) in the crater-fill deposits; (3) larger bodies of more slowly cooled igneous rock that occur as sills within the crater-fill deposits or intrude the subcrater rocks as dikes. In large structures, these latter bodies may be tens to hundreds of cubic kilometers in volume.

### 6.3.1. Small Glassy Bodies

Much of the impact melt, especially in small structures, occurs as individual discrete bodies in the allogenic breccia deposits in and immediately around the crater. In these units, the impact melt forms small, discrete, irregular bodies typically a few millimeters to about 20 cm in size, which may superficially resemble volcanic lapilli and bombs in size and shape. The material from the Ries Crater (Germany), which includes irregular, flattened, and aerodynamically sculptured bodies (*Fladen*), is perhaps the best-known and most-studied example of this type of material (*Hörz,* 1965; *von Engelhardt et al.,* 1969; *von Engelhardt and Graup,* 1984; *von Engelhardt,* 1990, 1997). However, similar objects occur in suevite breccias from numerous other impact structures.

These small melt bodies consist of rock and mineral fragments in a matrix of fresh or altered flow-banded glass. In thin sections, the rock and mineral fragments are frequently angular to sharp in outline, and their shapes indicate that they are broken clasts derived from the target rocks. The fragments also show a range of shock-metamorphic effects: fracturing, development of PDFs in quartz and feldspar, diaplectic glasses, and even incipient melting. The fragments occur in a matrix of glass (often brownish in thin section) which shows distinctive turbulent and heterogeneous flow structure, with compositionally different flow zones (Figs. 6.3, 6.4, and 6.5).

These impact glass bodies also show evidence of shock-produced temperatures far above those of conventional igneous processes. The most typical high-temperature indicator is the melting or decomposition of inclusions of refractory minerals derived from the target rocks (particularly quartz, zircon, and sphene), for which temperatures of >1400°–1800°C are required (Figs. 6.6, 6.7, and 6.8) (*El Goresy,* 1965, 1968; *French,* 1972, pp. 23–24). The most common indicator of high temperatures in these glasses is the presence of silica glass (**lechatelierite**), which has been formed from original quartz grains at temperatures above 1713°C. This lechatelierite often mixes incompletely with the other melt before cooling, producing clear streaks (**schlieren**) of pure silica in the glass (Fig. 6.3).

Small bodies of impact glass can be distinguished from normal volcanic products (e.g., obsidian, lapilli, and volcanic bombs) by their nonvolcanic features, evidence of extremely high temperatures (e.g., lechatelierite), and textures indicating strong disequilibrium [e.g., unabsorbed streaks or layers of pure silica (lechatelierite) in the glass]. Because of its high formation temperature, the presence of lechatelierite in apparently "volcanic" glasses is an especially reliable indicator that they are actually impact-produced melt rocks. (Lechatelierite is not found in any other natural materials except *fulgurites,* which are thin tube-like structures produced by the fusion of soil by lightning strikes. In particular, lechatelierite is not found in internally generated igneous rocks.) In addition, the rock and mineral inclusions in impact glasses are derived from the target rocks and not from cogenetic igneous rocks. These inclusions are broken fragments (**clasts**), not phenocrysts, and a small percentage of them (typically ~1%) display definite shock-metamorphic features: PDFs, isotropization, and high-temperature melting. Such clasts provide additional evidence for the impact origin of the melt rock.

### 6.3.2. Impact Melt Breccias

Large bodies of impact melt, which generally remain inside the crater, cool more slowly and may flow for significant distances before solidifying (*Dence,* 1971; *Grieve et al.,* 1977).

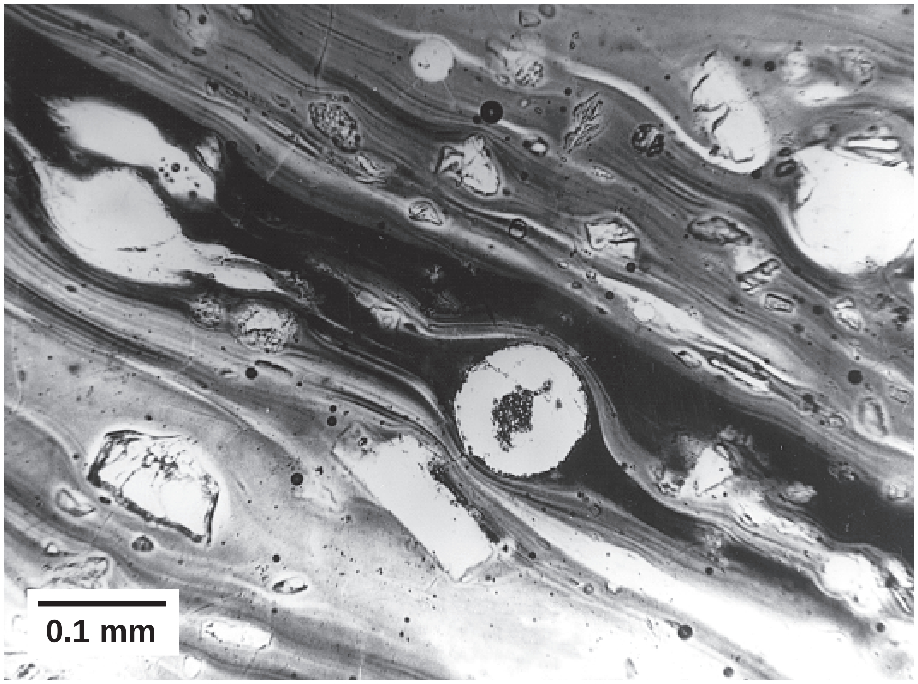

**Fig. 6.3. Impact melt rock; Fladen (glass) with schlieren.** Brownish, heterogeneous, flow-banded glass of granodioritic composition from glassy fragment (*Fladen*) in suevite breccia. The fragment contains spherical vesicles and irregular mineral fragments, mostly quartz. The matrix glass shows well-developed, locally laminar flow structure with discrete bands and streaks (*schlieren*) of high-silica glass (clear). Pure quartz glass (*lechatelierite*) also occurs as fluidal inclusions (clear; upper left), indicating shock melting of original quartz grains at temperatures above 1700°C. From suevite in Otting quarry, Ries Crater (Germany). Photo courtesy of W. von Engelhardt (plane-polarized light).

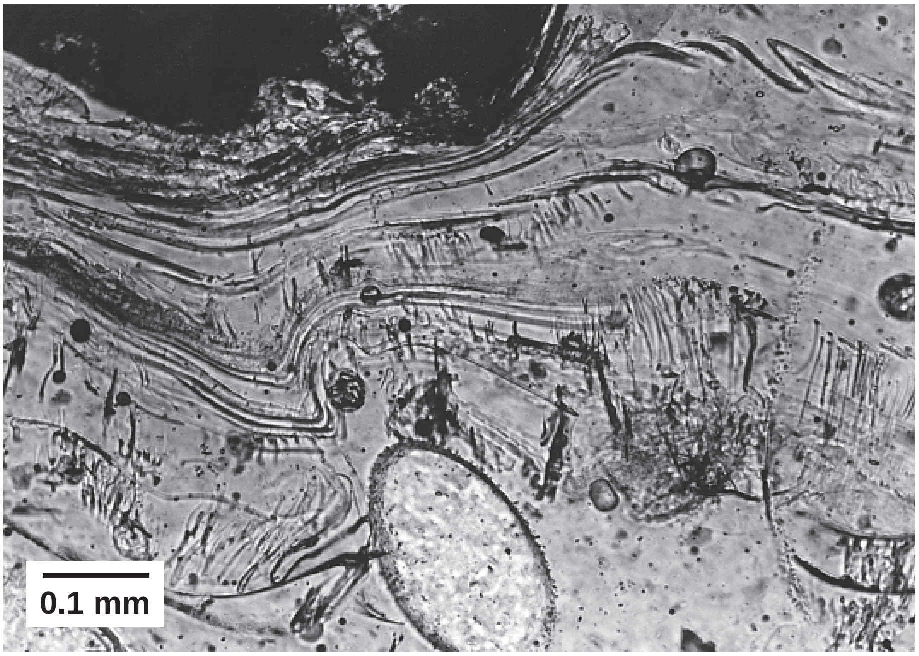

**Fig. 6.4. Impact melt rock; Fladen (glass) with schlieren.** Dense, heterogeneous, flow-banded glass from fragment in suevite breccia. Locally laminar flow-banding contains streaks and bands of quartz glass (*lechatelierite*) (clear) formed by shock melting of original quartz grains at temperatures above 1700°C. Part of an included quartz grain (dark) appears at top, with flow-banding distorted around it. A filled vesicle (white) appears at bottom. Drill core sample from West Clearwater Lake (Canada). Photo courtesy of M. R. Dence. Sample DCW-4A-63-170.7 (plane-polarized light).

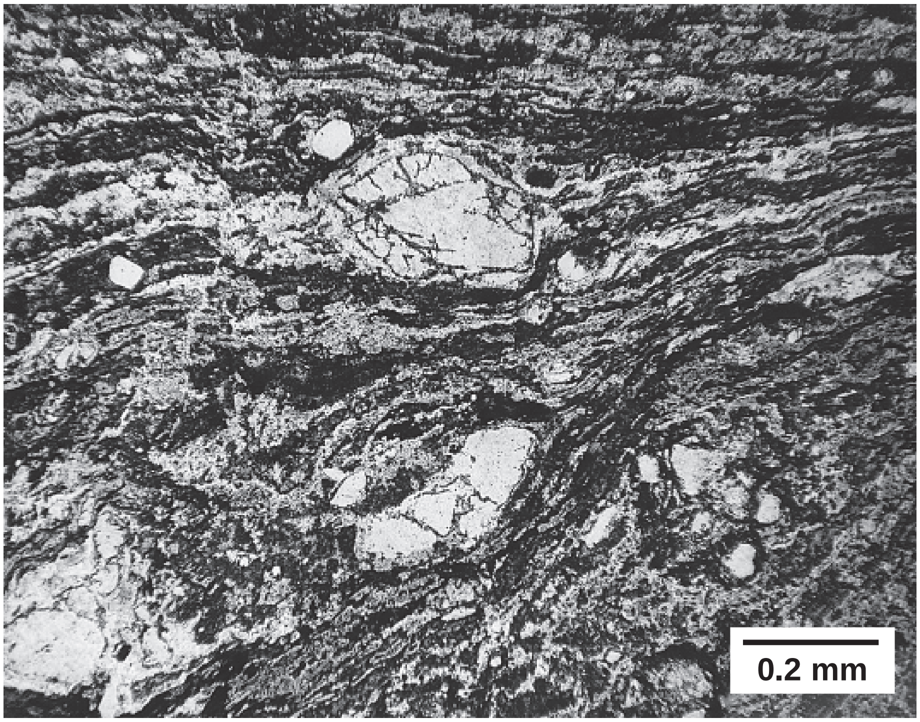

**Fig. 6.5. Impact melt rock; recrystallized Fladen (glass) with flow-banding.** Recrystallized glassy fragment from metamorphosed suevite breccia, containing rock and mineral clasts in heterogeneous, flow-banded recrystallized glassy material. Despite postimpact greenschist metamorphism, original heterogeneous flow banding is still preserved by the distribution of secondary minerals, chiefly quartz, feldspar, chlorite, and amphibole. The mineral clasts are rounded, angular, or irregular, and they lack the phenocryst shapes typical of glassy volcanic rocks. Quartz clasts (e.g., at top) rarely contain preserved indistinct PDFs, indicating that shock-deformation, melting, and mixing of rock fragments and melt were part of the same process. Sample from Onaping Formation, "Black Member," Sudbury (Canada). Sample CSF-67-64 (plane-polarized light).

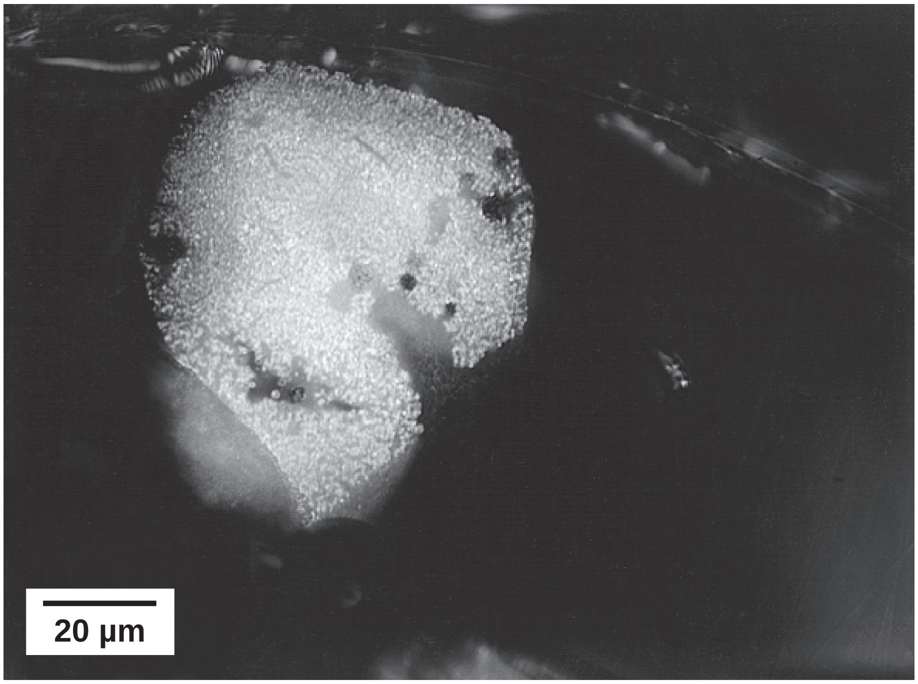

**Fig. 6.6. High-temperature effects; melted (decomposed) zircon.** A single grain of zircon ($ZrSiO_4$) from preimpact target rocks, incorporated into a fragment of high-temperature impact-melt glass ejected from the Aouelloul Crater (Mauritania). The original zircon is now melted and decomposed to a granular aggregate of the mineral baddeleyite ($ZrO_2$) (small bright dots) and silica glass. This decomposition occurs experimentally only at temperatures above 1750°C, and the presence of this reaction is clear evidence of high temperatures associated with meteorite impact events. Reflected light photomicrograph; courtesy of A. El Goresy.

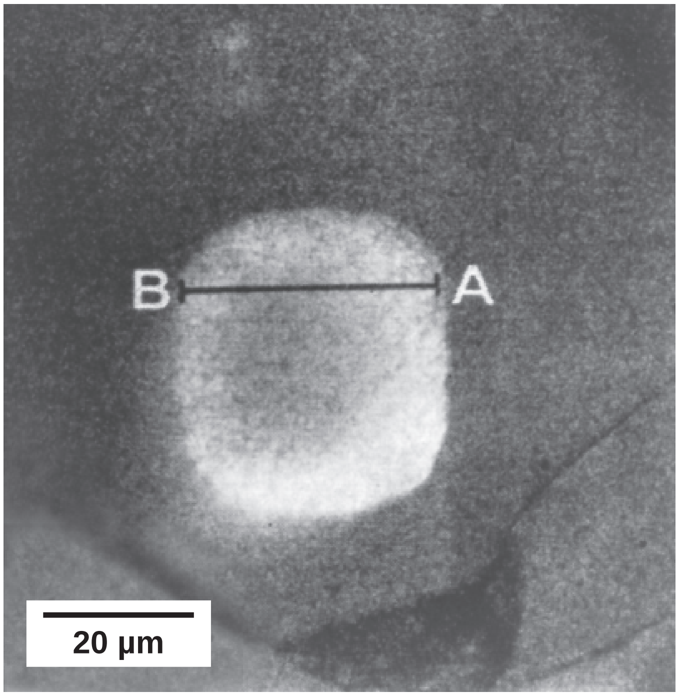

**Fig. 6.7. High-temperature effects; melted (decomposed) zircon.** Small rounded zircon grain, incorporated into impact-melt glass from preimpact target rocks. The rim of the grain shows partial decomposition of the zircon ($ZrSiO_4$) to baddeleyite ($ZrO_2$) (white, strongly reflecting), while the core of the grain consists of unaltered zircon (gray). From a fragment of impact glass from Möttingen, Ries Crater (Germany). Reflected light photomicrograph; courtesy of A. El Goresy.

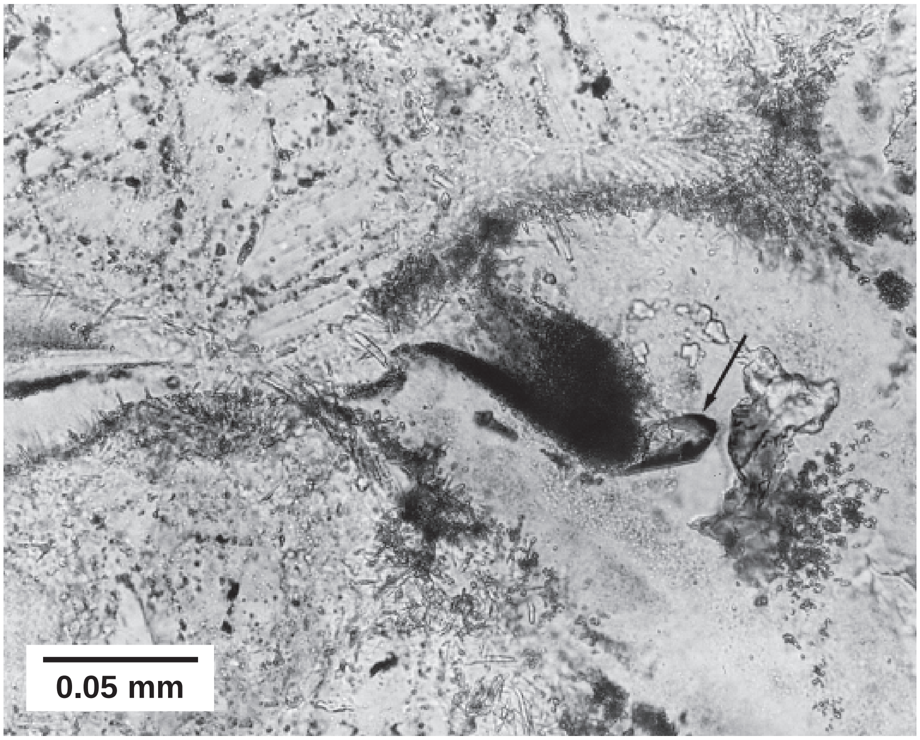

**Fig. 6.8. High-temperature effects; melted sphene.** Shocked and recrystallized quartzofeldspathic inclusion in metamorphosed suevite breccia. Original quartz (gray, higher relief; left) is largely unchanged. The grains are irregularly fractured and occasionally show decorated PDFs, e.g., two indistinct sets in the grain at upper left. Feldspar (clear, lower relief) is recrystallized. The clear needle-like minerals along the grain boundaries are probably secondary amphibole. Local melting and short-range flow are indicated by scattered dark flow-banded areas, possibly involving original opaque minerals. A small sphene grain (right center; arrow) (melting point ~1400°C) shows incipient melting, indicating unusually high localized temperatures. The right half of the grain preserves the original euhedral shape, while the left half has been converted into a spray of dark fine droplets that are being dispersed through the surrounding (plastic?) feldspar. Preservation of half the sphene grain indicates that the melting was both highly localized and rapidly quenched, as is typical for shock-metamorphic reactions. Granitic inclusion in Onaping Formation "Black Member," Sudbury (Canada). Sample CSF-67-72 (plane-polarized light).

During movement and cooling, the melt may mix with colder rock fragments, both shocked and unshocked. Where these fragments are abundant (e.g., >50–75 vol% of the total rock), their introduction causes the melt to cool and solidify rapidly. The resulting rock is an **impact melt breccia** (or melt-matrix breccia) containing rock and mineral fragments in an igneous matrix of glassy or crystalline impact melt (Figs. 6.9 and 6.10). Impact melt breccias occur in a wide range of crater sizes and locations. They form small irregular pods and lenses a few meters to tens of meters in size, within larger units of suevites or other crater-fill breccias. They may also form the marginal zones of larger bodies of clast-poor or clast-free impact melt. In these associations, the clast-bearing impact melt breccia may grade continuously into clast-poor impact melt (*Simonds et al.,* 1976, 1978a).

### 6.3.3. Large Crystalline Bodies (Dikes and Sills)

The formation of larger impact structures may generate several hundred to a few thousand cubic kilometers of impact melt, which collects within the crater to form large, slowly cooled, and generally crystalline bodies of igneous rock (*Dence,* 1971; *Grieve et al.,* 1977; *Simonds et al.,* 1978a,b; *Grieve et al.,* 1987; *Schuraytz et al.,* 1994). These impact melt bodies occur in two basic forms: (1) as horizontal sill-like bodies within the breccias that fill the craters, or (2) as dike-like bodies that penetrate the basement rock beneath the crater floor.

In small impact structures (D < 5 km), most of the impact melt produced is distributed through the crater-fill breccias as discrete fragments typically <10 cm in size, and any bodies of crystalline impact melt are correspondingly small. Examples include the small pool of melt in the center of the Brent Crater (Canada) (D = 3.8 km) (*Dence,* 1968; *Grieve,* 1978) (Fig. 3.7) and the possible dikes of impact melt just outside the rim of the Tenoumer Crater (Mauritania) (D = 1.9 km) (*French et al.,* 1970; *Fudali,* 1974).

However, in larger structures, most of the impact melt forms sill-like and dike-like bodies that can be extensive (Fig. 6.1). The layers of impact melt in several structures [e.g., West Clearwater (Canada) and Popigai (Russia)] are several hundred meters thick and contain 80 and 1750 km$^3$, respectively, of igneous rock (*Dence,* 1968; *Grieve and Cintala,* 1992). The well-known "Vredefort Granophyre" (formerly called the "Bronzite Granophyre") at Vredefort (South Af-

**Fig. 6.9. Impact melt rock; breccia, dike.** Exposure of dike of impact melt unit ("Bronzite Granophyre" or "Vredefort Granophyre") from Vredefort (South Africa) emplaced in preimpact granitic basement rocks. The dike is an inclusion-rich breccia containing numerous light-colored large and small fragments (dominantly quartzite, with minor granite) in a dark, massive, coherent matrix of finely crystalline melt rock. Farm Lesutoskraal 72, near the center of the uplifted basement rocks. Photo from *Nel* (1927, Plate XIV).

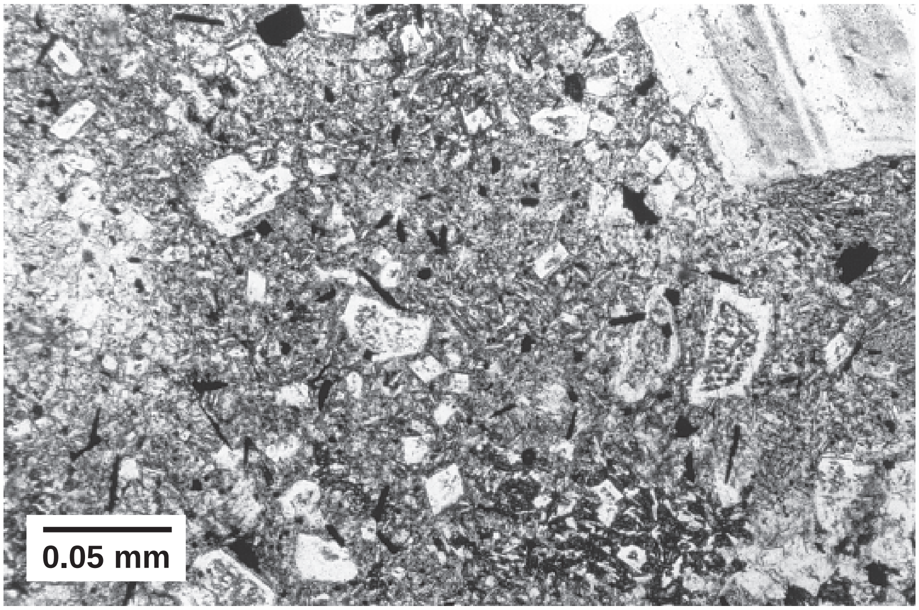

**Fig. 6.10. Impact melt rock; breccia.** Clast-rich melt-matrix breccia consisting of numerous mineral clasts (light-colored) (chiefly plagioclase feldspar from basement rocks), in a matrix of finely crystalline (plagioclase-pyroxene-quartz) melt. Larger plagioclase clasts show reaction rims and display partial digestion in the melt. From Mistastin Lake (Canada). Photograph courtesy of R. A. F. Grieve (plane-polarized light).

rica), a unit that is increasingly regarded as an impact melt (*Dence,* 1971; *French and Nielsen,* 1990; *Therriault et al.,* 1996; *Koeberl et al.,* 1996c), occurs only as small dikes in the deeply eroded basement of the structure. In this case, the presently preserved melt volume is probably only a small surviving fraction of the total impact melt ($10^3$–$10^4$ km$^3$) originally generated during the formation of the Vredefort structure (Fig. 6.9). Nearly all the original impact melt, which probably formed a thick sill-like unit within the original crater, has been removed by erosion.

The largest presently known body of impact melt may be the voluminous Sudbury Irruptive in the Sudbury impact structure (Canada). New geochemical and modeling studies suggest that the entire Irruptive was produced as a single body of impact melt during formation of the structure (*Faggart et al.,* 1985; *Grieve et al.,* 1991a; *Stöffler et al.,* 1994; *Grieve,* 1994; *Deutsch et al.,* 1995). If this view is correct, the Sudbury structure contains an impact melt body >8000 km$^3$ in volume, with the impact melt occurring both as the sill-like main body of the Irruptive and as a group of dikes ("offsets") that extend from the main Irruptive into the surrounding subcrater rocks (*Ostermann et al.,* 1996; *Wood and Spray,* 1998).

## 6.4. IMPACT MELT IN DISTAL EJECTA

Although virtually all the melt generated in an impact event is deposited in and around the resulting crater, a very small fraction (perhaps <0.1 vol%) of impact melt may be ejected from the crater as millimeter- to centimeter-sized bodies of pure melt that, chilled rapidly to glass, are deposited as part of a layer of **distal ejecta** hundreds or thousands of kilometers away from the impact site. Two kinds of such glassy material in distal ejecta can be conveniently distinguished: (1) **spherules** of fresh or altered glass, and (2) **tektites** and **microtektites**. These unusual glassy bodies, especially tektites and microtektites, have been the objects of active, intense, and frequently controversial study (for reviews see *O'Keefe,* 1963, 1976; papers in *L. D. Pye et al.,* 1984 and *Konta,* 1988; *Koeberl,* 1986, 1994a). Several different types of glassy distal ejecta have been recognized, but future studies will probably produce major changes in both definitions and formation mechanisms.

At present, it is generally accepted that the formation and widespread distribution of these objects requires both intense (superheated) melting at the impact site, followed by high-velocity ejection from it, but the exact processes of melting and transport are not well understood. One possibility is that **jetting** of highly shocked, superheated melt occurs at the interface between the projectile and the target during the initial part of the contact/compression stage (*Kieffer,* 1975; *Melosh,* 1989, pp. 51–53; *Melosh and Vickery,* 1991). Other possible mechanisms may involve dispersal of subsequently shock-melted material by an expanding vapor plume from the impact site (*Melosh,* 1989, pp. 68–69; *Alvarez et al.,* 1995). Any formation mechanism must explain chemical data that suggest that these glassy objects are derived from the near-surface parts of the section of target rocks at the impact site (e.g., *von Engelhardt et al.,* 1987). It is also accepted that Earth's atmosphere must be briefly removed, or at least largely dispersed, to permit these fragile molten objects to travel long distances without being destroyed, implying that the formation and distribution of such objects must be restricted to impact events large enough to remove (at least temporarily) the atmosphere above the impact site.

### 6.4.1. Spherules

The formation of millimeter-sized glassy spherules from shock-melted droplets of impact melt appears to be a typical process in impact events. Such spherules are especially common in samples of lunar surface materials (e.g., *Taylor,* 1975, pp. 67–78; *Symes et al.,* 1998), where their abundance may reflect the peculiar conditions of the lunar environment: lack of atmosphere and the possibility of numerous impacts by small or microscopic objects. Spherules have also formed in at least some terrestrial impact events, and spherules of both glass and melted meteoritic metal have been found in young and well preserved craters like the Barringer Meteor Crater (Arizona) (*Krinov,* 1966, pp. 104–107 and 113–119), Wabar (Saudia Arabia) (*Krinov,* 1966, pp. 19–24; *Mittlefehldt et al.,* 1992), and Lonar (India) (*Murali et al.,* 1987). However, spherules have not been widely observed in preserved impactites associated with most terrestrial impact structures, possibly because such ejected molten particles do not survive the disruptive effects of the atmosphere, or because such particles are quickly destroyed by weathering and erosion. A few occurrences of spherule-like objects have been described in the glassy breccias associated with impact structures (Fig. 6.11) (*Graup,* 1981; *French,* 1987). In contrast, spherules are becoming increasingly recognized as an important component of the distal ejecta layer from large impact structures, and they may be found at great distances from the impact site.

The best known and most-studied spherule deposit is the distal ejecta layer (K/T boundary layer) from the Chicxulub structure (Mexico), which is distributed over distances of several thousand kilometers from the impact site and contains a significant component of fresh and altered spherules of impact melt (*Montanari et al.,* 1983; *Sharpton et al.,* 1992;

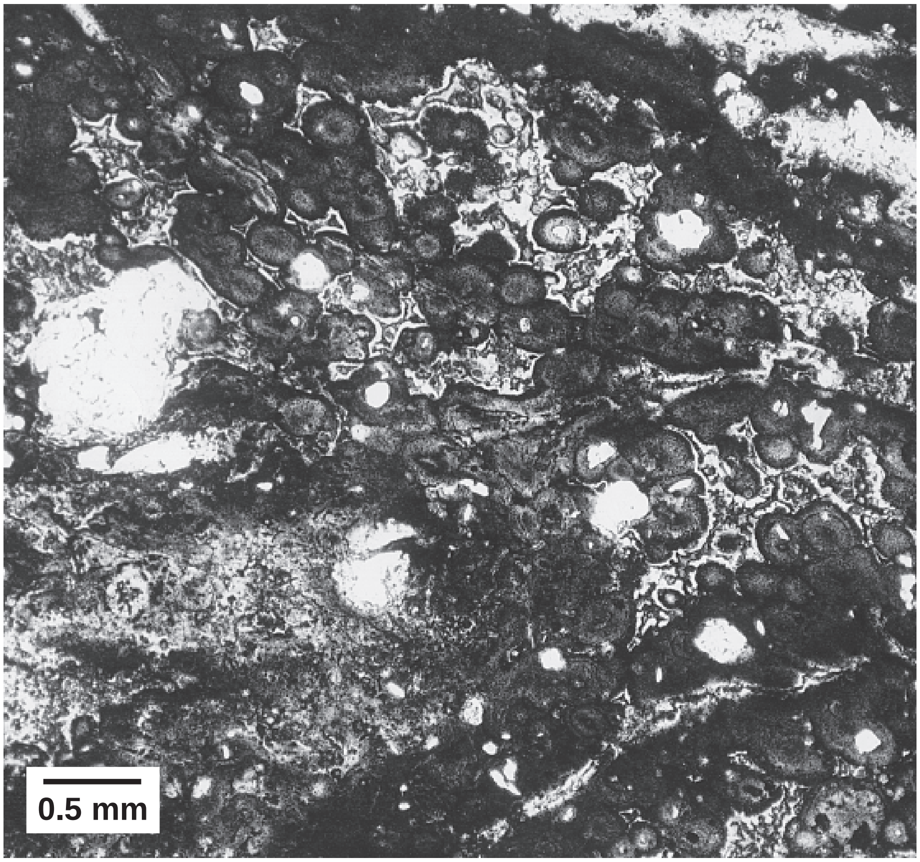

**Fig. 6.11. Impact melt rock; spherulitic glass rim on rock fragment.** Heterogenous mixture of recrystallized spherulitic glass and small rock and mineral fragments, forming a heterogeneous glassy rim on a larger rock fragment core. The composite inclusion occurs in a metamorphosed suevite breccia. The small rock fragments, chiefly quartz and feldspar, are generally angular and irregular in shape, and phenocryst textures typical of glassy volcanic rocks are not observed. Despite postimpact greenschist metamorphism, original heterogeneity of the glass is preserved by the distribution of secondary minerals, chiefly quartz, feldspar, chlorite, and amphibole. The small red-brown spherical bodies frequently contain a smaller central crystal fragment, suggesting that they were discrete droplets before being incorporated into the rim around the larger core fragment. If so, the texture may result from accretion of glass and rock fragments during ballistic ejection. (The texture may also represent subsequent in-place devitrification or recrystallization around the mineral fragment nucleus.) Granitic rock fragment from Onaping Formation "Black Member," type locality at Onaping Falls (Highway 144, Dowling Township), northwestern corner of Sudbury structure (Canada). Sample CSF-66-50-1-D (plane-polarized light).

*Pollastro and Bohor,* 1993; *Bohor and Glass,* 1995; papers in *Sharpton and Ward,* 1990 and *Ryder et al.,* 1996). The association of these spherules with shocked quartz and an iridium anomaly establishes them as definite impact melt products, while chemical and isotopic studies have firmly established their connection to the target rocks of the Chicxulub structure (*Sigurdsson et al.,* 1991a,b). Massive spherule layers, as much as a meter thick, have been reported from the Precambrian, but they lack any definite shock-metamorphic effects and are more problematic (*Lowe and Byerly,* 1986; *French,* 1987; *Lowe et al.,* 1989; *Simonson,* 1992; *Koeberl et al.,* 1993; *Simonson and Davies,* 1996; *Simonson et al.,* 1997). Their impact origin has not been definitely established, nor have they been linked to any known impact structure.

Spherule layers have important potential for recognizing and locating other large impact structures in the future. The deposits can be detected over large areas, they can be identified as impact products, and they contain isotopic and geochemical clues that can help locate the source crater and establish its age.

### 6.4.2. Tektites and Microtektites

Tektites and microtektites are unique and long-known small glassy objects that have a long history of study and controversy (for reviews, see *O'Keefe,* 1963, 1976; *Glass,* 1984, 1990; *Koeberl,* 1986, 1990, 1992, 1994a). They are typically black in color, although some varieties are greenish, brownish, or grayish. The larger (centimeter-sized) **tektites**, which occur on land, are associated with smaller (≤1 mm) **microtektites**, preserved in deep-sea sediments. Although tektites and microtektites resemble volcanic glasses in form, they have several geologically unusual distinctive characteristics. They are completely glassy, with no microlites or phenocrysts. They are typically high in silica (>65 wt%), but their chemical and isotopic compositions are not volcanic and are closer to those of shales and similar sedimentary rocks. Also unlike volcanic glasses, tektites contain virtually no water (<0.02 wt%), and their flow-banded structure includes particles and bands of lechatelierite, melted silica glass. A few tektites contain partly melted inclusions of shocked and unshocked mineral grains (quartz, apatite, zircon) as well as coesite (*Glass and Barlow,* 1979).

In the best-preserved tektite occurrence, in Southeast Asia, four types of tektite material have been recognized: (1) **splash-form tektites**, which are centimeter-sized objects shaped like spheres, ellipsoids, dumbbells, and other forms characteristic of isolated molten bodies; (2) ablated splash-form tektites (**buttons**), which display a secondary ring produced during high-speed reentry of a solidified splash-form tektite into the atmosphere; (3) **Muong Nong tektites**, which are generally larger (≥10 cm), irregular, and layered; and (4) **microtekites**, which are small (≤1 mm) spherules found as concentrations in specific layers of deep-sea sediments.

Tektites and microtektites are distributed over large areas (**strewnfields**) of Earth's surface. Four strewnfields are known at present, distinguished by differences in location, age, and (to some extent) the characteristics of the tektites and microtektites found. The strewnfields and their ages are: (1) *Australasian* or southeast Asian (australites, indochinites, phillipinites), age 0.8 Ma; (2) *Ivory Coast (Africa),* age ~1.1 Ma; (3) *Central European* (formerly *Czechoslovakian*), age 15.0 Ma; (4) *North American,* age ~35 Ma. Both the areas and tektites masses included in the strewnfields can be large. The Australasian strewnfield covers about 50 × $10^6$ km$^2$, or about one-tenth of the area of the Earth, and it is estimated to contain $10^8$ T of tektite material (*Glass,* 1990). The North American strewnfield has an area of about 9 × $10^6$ km$^2$, and contains $10^8$–$10^9$ T of tektite material (*Koeberl,* 1989). Although large, the strewnfield masses correspond to a volume of <1 km$^3$ of impact melt, probably <1–2% of the total amount of melt formed during the event.

Tektites have been controversial objects since their discovery, and both their origin and source have been hotly debated for more than a century (*O'Keefe,* 1963, 1976, 1994; *Glass,* 1990; *Taylor and Koeberl,* 1994). However, the current scientific consensus is that tektites and microtektites are impact melt ejected from terrestrial impact craters. An impact origin is supported by their nonvolcanic chemistry, the presence in tektites of high-pressure minerals (coesite), and features indicating unusually high temperatures (lechatelierite, decomposed zircon) (*Glass and Barlow,* 1979; *Glass,* 1990). The recent detection, in Ivory Coast tektites, of a chemical signature from an extraterrestrial projectile (*Koeberl and Shirey,* 1993) provides strong independent evidence for an origin in a terrestrial impact event.

A terrestrial source for tektites has been increasingly supported by their chemical similarity to terrestrial sediments, by the presence in tektites of relict mineral inclusions (quartz, zircon, rutile, chromite, and monazite) characteristic of sedimentary rocks, and by accumulating geochemical and isotopic studies that indicate a crustal and sedimentary source. Three of the four tektite strewnfields have been linked, with varying degrees of confidence, to established impact craters of similar age (*Glass,* 1990; *Koeberl,* 1990): the Ivory Coast strewnfield to the Bosumtwi (Ghana) structure (D = 10.5 km) (*Koeberl et al.,* 1997b), the Central European field to the Ries Crater (Germany) (D = 24 km), and the North American strewnfield to the recently recognized Chesapeake Bay Crater (USA) (D = 90 km) (*Koeberl et al.,* 1996a). (This latter strewnfield was also deposited close to — but about a quarter of a million years before — a significant, although moderate, extinction event at the Eocene/Oligocene boundary.) The absence of any obvious impact structure connected to the young and widespread Australasian strewnfield is a continuing problem. Although several characteristics of the strewnfield itself suggest that the source crater is located somewhere in a relatively small region of Indochina, no candidate impact structure has yet been identified.

Despite the growing consensus on tektite origins, the mechanics of their formation and the factors that govern their distribution are still not well understood. Exactly when do tektites form during the impact process, and how are they distributed so widely? What is the relation of tektites to other types of impact melts, and especially to similar dense glasses found in and around certain craters? Why do tektites appear to form only in a few craters, although numerous young structures of the required minimum size (probably ≥10 km diameter, based on the diameter of the Bosumtwi Crater) are known? What are the relations of tektite-forming events to other major terrestrial changes like extinctions and magnetic reversals? It is clear that the small fraction of impact melt that produces tektites during impact events will continue to generate a large amount of discussion and research.

### 6.4.3. Miscellaneous Impact Glasses

Other types of unusual glass, located in widely different regions of the Earth, have gradually been recognized as impact melts. These glasses appear as small (generally centimeter-sized) irregular bodies that may be scattered over areas of a few square kilometers to >100 km$^2$. Their textures vary from dense to vesicular and slaggy, some contain mineral and rock inclusions, and colors range from blackish to pale green. These glassy objects have been relatively little studied (see papers in *L. D. Pye et al.,* 1984 and *Konta,* 1988), and many questions remain about their sources, methods of formation, and possible relationships to other kinds of impact melt.

Some of these occurrences are associated with small, young impact craters. The dense, greenish **Aouelloul glass** is found as small (centimeter-sized) irregular bodies immediately outside the Aouelloul Crater (Mauritania) (D = 0.39 km; age 3.1 Ma), and it appears to have been formed by complete fusion of the local sandstone (*Koeberl et al.,* 1998). The more vesicular and irregular **Darwin glass** (age 0.75 Ma) is distributed over a wider area, but may be associated with the Darwin Crater (Australia), a small (D = 1 km) possible impact structure (*Ford,* 1972; *Meisel et al.,* 1990). In two other cases, no candidate impact crater has yet been identified for the glasses. The **Libyan Desert glass** (age ~29 Ma) is a high-silica (>95 wt%), yellow-green to brownish glass found over a wide area in western Egypt (*Weeks et al.,* 1984; *Storzer and Koeberl,* 1991). An impact origin is generally accepted for this glass, on the basis of the high melting temperature required for such a silica-rich composition and the presence of lechatelierite and decomposed zircons in a few samples. However, a target rock of virtually pure orthoquartzite is required, and no source crater has yet been identified. The little-known **urengoites** and other glasses from western Siberia (Russia) also appear to be high-silica impact melts (*Deutsch et al.,* 1997), but their geochemical and isotopic characteristics have not been matched with any known impact crater.

## 6.5. RECOGNITION OF IMPACT MELT ROCKS

Despite their exotic origin, impact melt rocks are true igneous rocks that have formed by the cooling and crystallization of high-temperature silicate melts, and they often

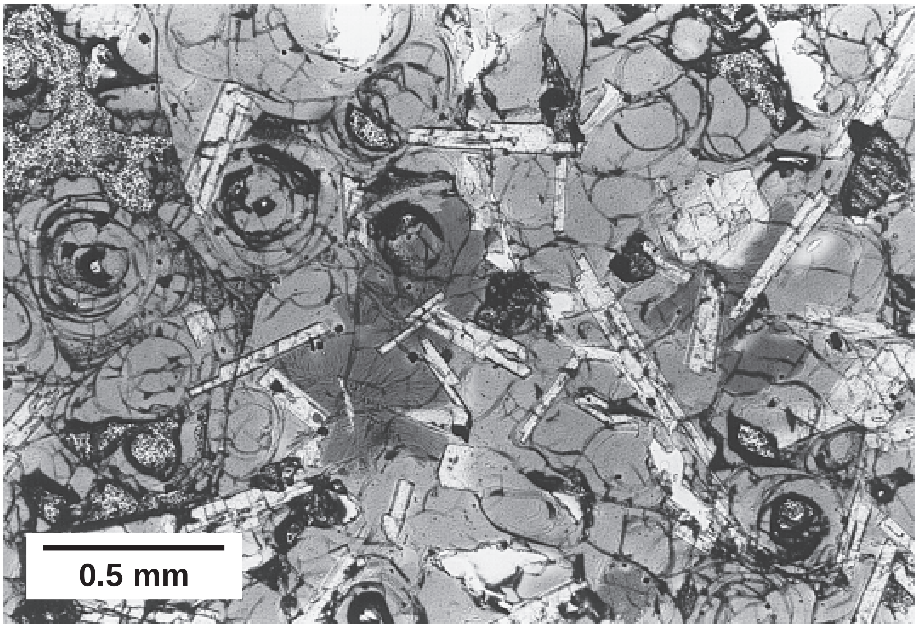

**Fig. 6.12. Impact melt rock; glassy, with feldspar crystals.** Glassy impact melt rock with euhedral quench crystals of feldspar in a partly devitrified glassy matrix. The brownish glassy matrix shows perlitic devitrification textures consisting of circular cracks and the growth of finer spherulitic crystals (feldspar?). This material was long considered an unusual extrusive igneous rock ("Dellenite"). Identification as an impact melt has been based on its association with shock-metamorphosed rocks and the presence of anomalously high siderophile elements (e.g., iridium) in the melt rock itself. Sample from exposures of crater-filling impact melt layer at Lake Dellen (Sweden). Specimen courtesy of A. Deutsch. Sample SDDe-3/4-1 (plane-polarized light).

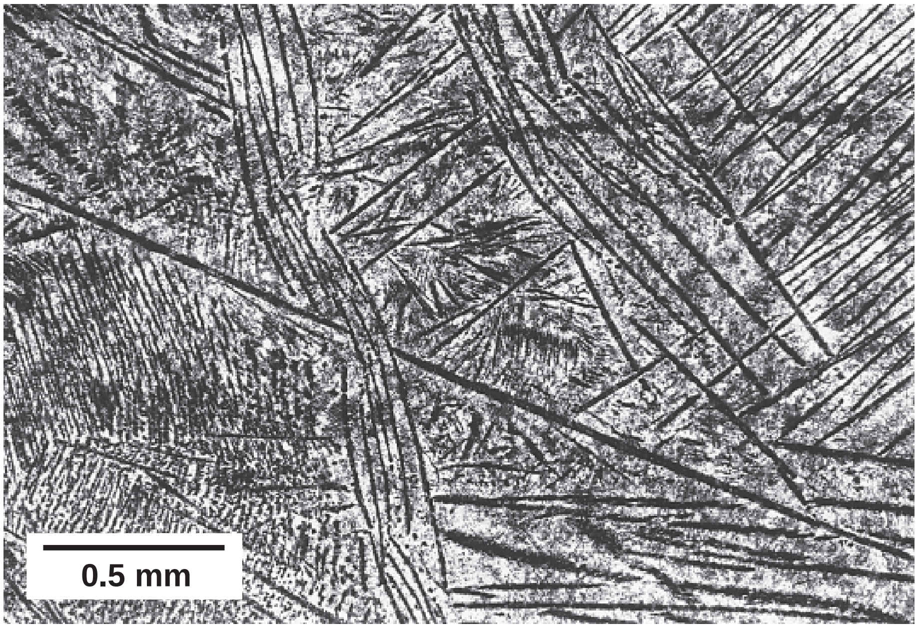

**Fig. 6.13. Impact melt rock; crystalline, with pyroxene (?) quench crystals.** Recrystallized glassy impact melt rock with well-developed quench textures consisting of highly elongate pyroxene(?) crystals in a fine-grained recrystallized matrix. The highly elongate strings and networks of narrow crystals are typical for rapidly cooled igneous melts formed by both conventional volcanism and impact events. Sample from the Charlevoix structure (Canada). Specimen courtesy of J. Rondot. Sample CHR-68-1 (plane-polarized light).

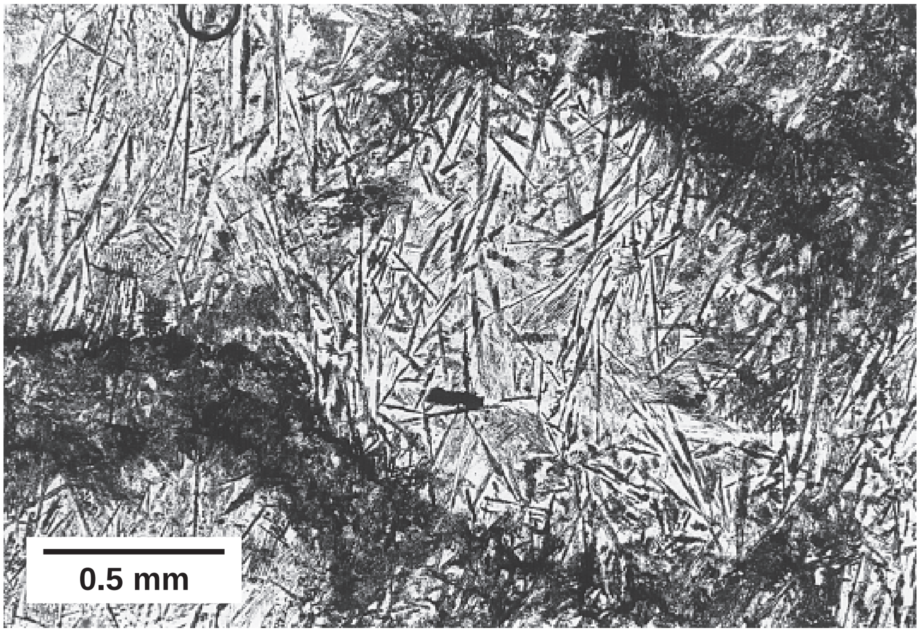

**Fig. 6.14. Impact melt rock; crystalline, with pyroxene (?) quench crystals.** Glassy impact melt from a 1-m-wide dike cutting metamorphosed suevite. Despite postimpact greenschist metamorphism, the rock still preserves well-developed quench textures consisting of highly elongate subparallel pyroxene(?) crystals (now possibly secondary amphibole?) in a fine-grained recrystallized matrix. Such strings and networks of elongate quench crystals are typical for rapidly cooled igneous melts formed by both conventional volcanism and impact events. In this sample, original igneous textures are preserved, together with a spherulitic texture probably produced during devitrification or recrystallization of the glassy matrix. Sample from the Onaping Formation "Black Member" at the type locality, Onaping Falls (Highway 144, Dowling Township), northwestern corner of Sudbury structure (Canada). Sample CSF-68-18 (plane-polarized light).

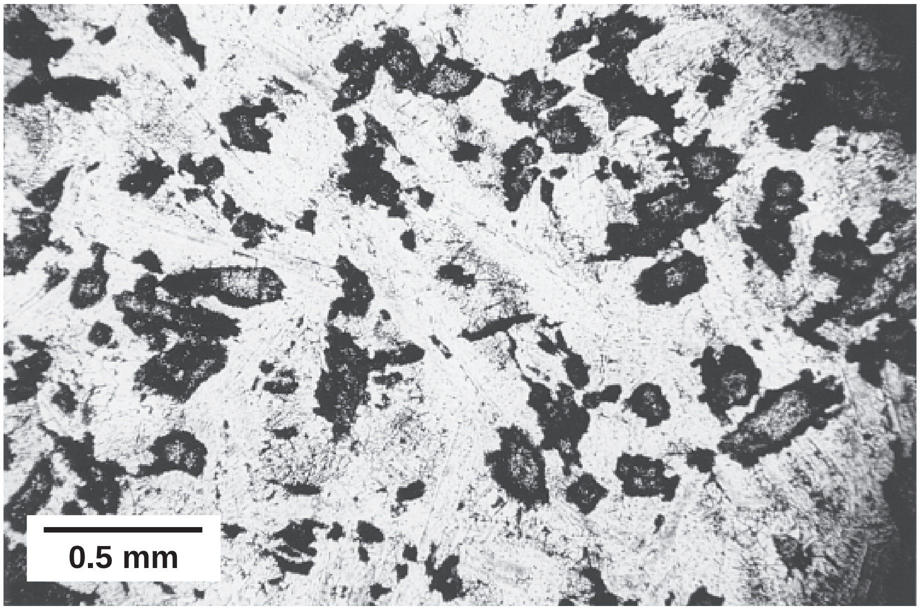

**Fig. 6.15. Impact melt rock; crystalline, granular.** Typical crystalline impact melt rock from a dike cutting preimpact basement granites near the center of the Vredefort structure (South Africa). This granular variety of the so-called "Bronzite Granophyre" shows a typical igneous texture, with stubby orthopyroxene crystals (gray), apparently rimmed by secondary amphibole (dark gray), together with elongate feldspar, quartz, and minor fine-grained granophyric quartz-feldspar intergrowths (compare with Figs. 6.16 and 6.17). Sample from dike cutting basement granite near town of Vredefort, South Africa (farm Holfontein 44?). Specimen courtesy of R. B. Hargraves. Sample AVH-68-2 (plane-polarized light).

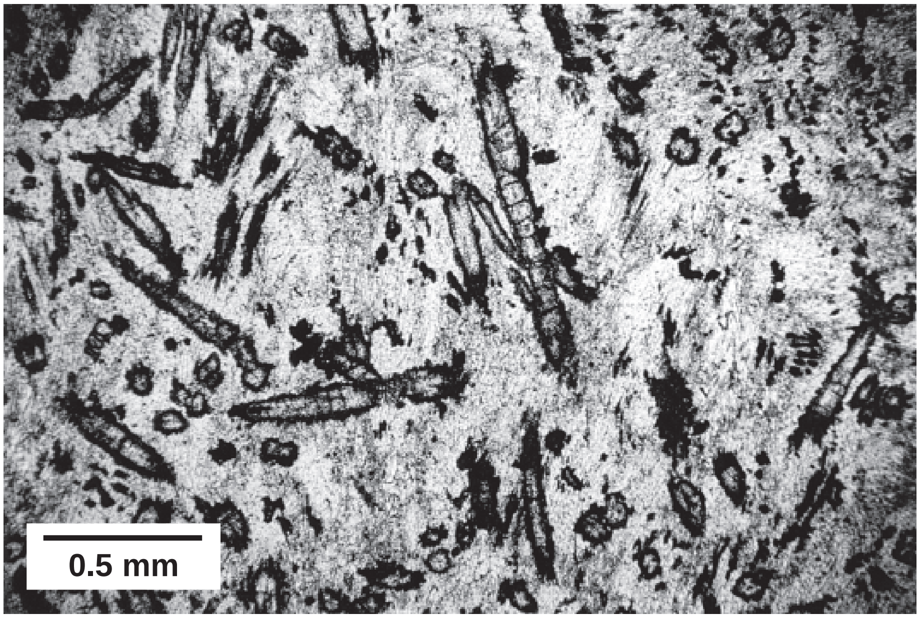

**Fig. 6.16. Impact melt rock; crystalline, spherulitic.** Typical crystalline impact melt from a dike cutting preimpact basement granites. This spherulitic variety of "Bronzite Granophyre" shows a typical igneous texture, with large elongate orthopyroxene crystals (gray; high relief), in a groundmass of fine-grained granophyric feldspar and quartz (compare with Figs. 6.15 and 6.17). Sample from farm Holfontein 44, south of Vredefort, South Africa. Sample AV81-58 (plane-polarized light).

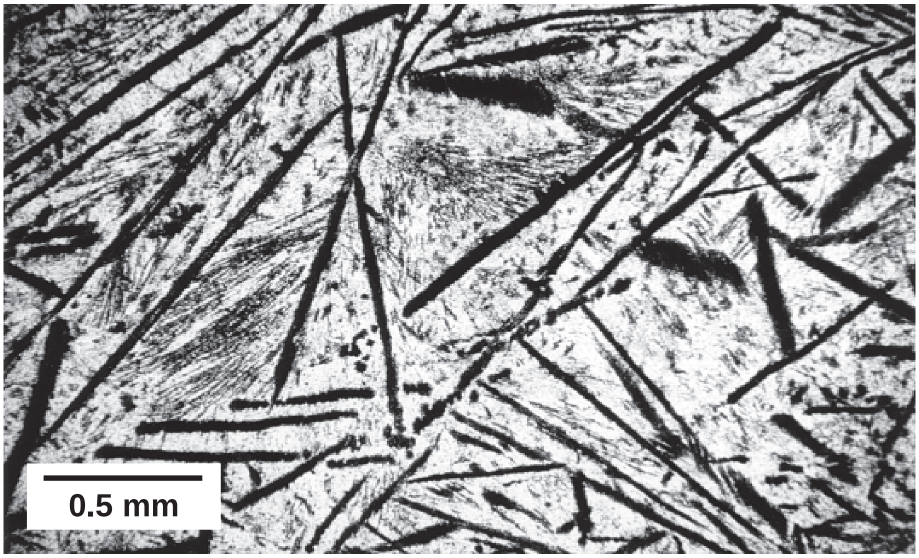

**Fig. 6.17. Impact melt rock; crystalline, with quench textures.** Typical crystalline impact melt from a dike cutting preimpact basement granites. This variety of "Bronzite Granophyre" shows a typical igneous texture, with highly elongate quench crystals of orthopyroxene (gray), in a fine spherulitic groundmass of intergrown feldspar and quartz (compare with Figs. 6.15 and 6.16). Sample from farm Koppieskraal, Vredefort structure (South Africa). Sample AV81-61A (plane-polarized light).

**Fig. 6.18. Impact melt rock; crystalline, inclusion-poor.** Well-crystallized impact melt, showing isolated clasts of plagioclase feldspar (bottom and lower right) in a fine-grained melt matrix consisting of well-crystallized plagioclase, poikilitic pyroxene, quartz, and opaque minerals. The clasts (xenocrysts) are generally partly digested, but new feldspar rims (clear) have developed on the altered cores (cloudy, gray). Sample from thick annular layer of impact melt preserved at Mistastin Lake (Canada). Photo courtesy of R. A. F. Grieve (plane-polarized light).

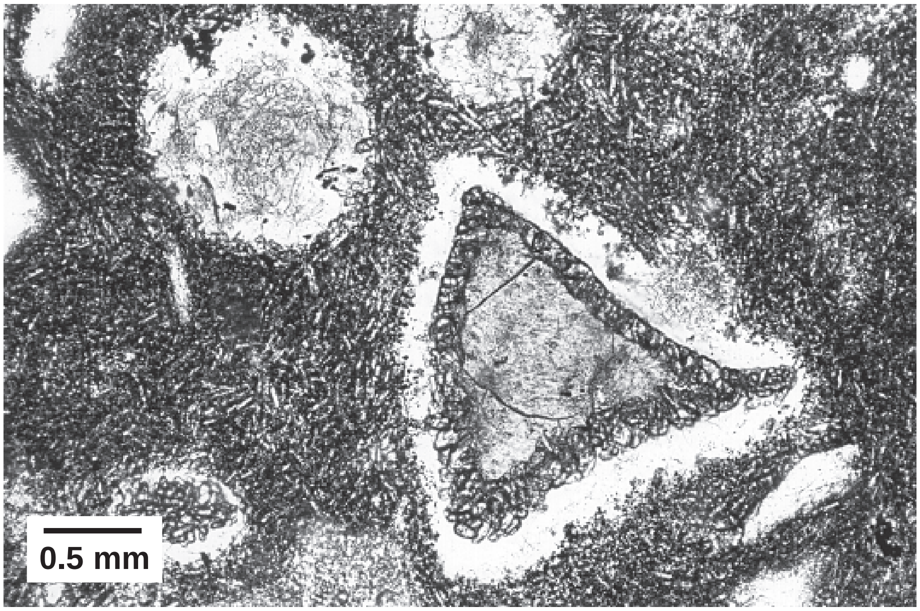

**Fig. 6.19. Impact melt rock; fine-crystalline, with pyroxene coronas.** Completely crystalline impact melt rock, with clasts of plagioclase and quartz in a very fine-grained matrix consisting of plagioclase, poikilitic pyroxene, quartz, and opaque minerals. Distinctive coronas or "necklaces" of small pyroxene crystals have developed around quartz grains by reaction between the quartz xenocrysts and the melt. The triangular quartz grain shown is surrounded by a thin rim of small pyroxene crystals (gray, high relief), beyond which is a rim of clear glass that has been depleted in iron and other coloring agents to form the pyroxene. Sample from thick annular layer of impact melt within the Mistastin Lake structure (Canada). Photo courtesy of R. A. F. Grieve (plane-polarized light).

exhibit textures and mineral compositions that are identical to those of typical endogenic volcanic and intrusive rocks. Impact melt rocks may range in character from largely glassy rocks containing quench crystallites (Figs. 6.12, 6.13, and 6.14) to completely crystalline and even coarse-grained igneous rocks that may show a wide range of typical igneous textures in even small bodies (Figs. 6.15, 6.16, 6.17, and 6.18). Because of these similarities in mineralogy and texture, it may often be impossible to distinguish between an isolated specimen of impact melt and a normal igneous rock on the basis of petrographic observations alone.

The similarities between impact melt rocks and endogenic igneous rocks have been one factor in the prolonged controversies over the origin of many now-accepted impact structures. Nevertheless, several decades of field and laboratory studies have now produced some generally reliable criteria for recognizing impact melt rocks and for differentiating them from endogenic igneous rocks.

The best field evidence for the origin of an impact melt unit is an intimate association with more distinctive shock-metamorphosed rocks. Impact melt bodies that occur as dikes cutting the subcrater basement rocks may be closely associated with pseudotachylite breccias or (more convincingly) with shatter cones and microscopic shock-deformation effects in the subcrater rocks that provide definite evidence of an impact origin. Above the crater floor, impact melt bodies of various sizes are intermingled with breccias that contain distinctively shock-metamorphosed rock and mineral fragments; such an association is also clear evidence for impact.

On the scale of individual hand specimens, the most definitive characteristic of impact melts is not the igneous crystallization textures, but the nature and appearance of included rock and mineral clasts. These fragments are derived from the target rocks; they do not resemble cogenetic volcanic materials. Furthermore, because the clasts are exotic (*xenoliths* and *xenocrysts*), they may be out of equilibrium with the melt and may develop reaction textures against it. Distinctive overgrowths of compositionally different feldspar have formed on feldspar xenocrysts in the impact melt from the Brent Crater (Canada) (*Grieve,* 1978). Another common reaction texture in impact melts is the formation of "necklaces" of small pyroxene crystals against quartz clasts (Fig. 6.19). Although common in impact melts, such reaction textures also form around xenocrysts in some endogenic igneous rocks and do not specifically indicate an impact origin.

More convincing, preserved target rock fragments in impact melt rocks often contain definite shock features such as PDFs in quartz. Other textures, which reflect extremely high formation temperatures, also provide convincing evidence of impact. Feldspar xenocrysts may show unusual melting and recrystallization textures produced at high temperatures (*Ostertag and Stöffler,* 1982; *Bischoff and Stöffler,* 1984). Some rapidly cooled impact melt rocks may also preserve millimeter-sized patches of lechatelierite, produced from the high-temperature melting of quartz grains (Figs. 6.20 and 6.21) (*French et al.,* 1970; *Carstens,* 1975; *Stöffler and Langenhorst,* 1994). When such bodies of lechatelierite cool, a combination of thermal stress and crystallization produces

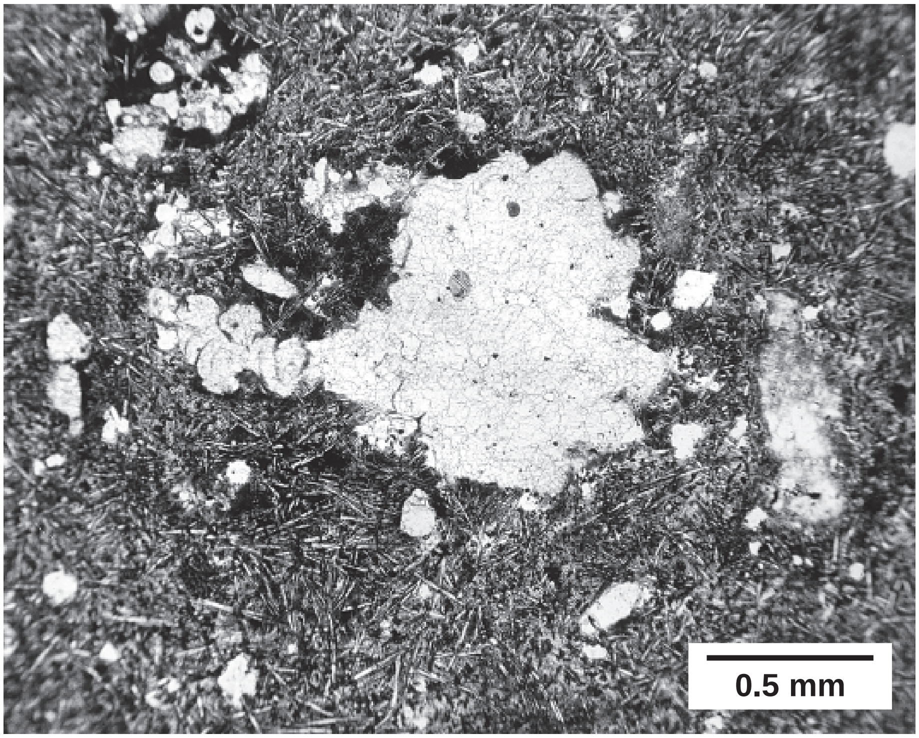

**Fig. 6.20. Impact melt rock; partly crystalline, with lechatelierite.** Finely crystalline impact melt rock, containing inclusions of quartz glass (*lechatelierite*). Irregular inclusions of clear lechatelierite (e.g., center, light gray) occur in a partly crystalline matrix consisting of pyroxene, elongate feldspar laths (white), opaque minerals, and interstitial brown glass. The contact between lechatelierite and brownish matrix glass is irregular and interpenetrating, indicating that both glasses were originally molten at the same time. The lechatelierite displays a typical crackled (*Ballen*) texture produced by devitrification of the silica glass to silica minerals. The lechatelierite probably originated by shock-melting of original quartz grains, at temperatures above 1700°C, and was incorporated into the more abundant impact melt formed by the larger volume of target rock. The presence of small unaltered quartz grains (small scattered white areas) in the impact melt indicates that the lechatelierite did not form by simple in-place thermal melting in a very-high-temperature melt. Sample from a possible dike of impact melt located on the rim of Tenoumer Crater (Mauritania). Specimen courtesy of R. S. Dietz. Sample TM-3-1 (plane-polarized light).

a distinctive "crackled" pattern of curved fractures in the original glass (Figs. 6.20 and 6.21). This **Ballen texture** is a distinctive feature of lechatelierite in impact melt rocks.

Impact melt samples that lack distinctive shock-metamorphic textures can still be identified by a variety of geochemical signatures. One test is to compare the impact melt composition with that of the target rocks. Because impact melts are produced predominantly from target rocks, with only a minor (usually ≤1%) projectile contribution, their chemical and isotopic compositions should correspond to the average compositions of the local bedrocks. The demonstration of such compositional matches, especially when the composition cannot be easily produced by endogenic processes, is a strong (although not absolute) indication of an impact origin. Such comparisons can be more conclusive if there is a chemically or isotopically unusual component in the target rocks that can be recognized in the composition of the impact melt (*French and Nielsen,* 1990).

More definite evidence of an impact origin can be obtained by analyzing the impact melt for **siderophile** elements such as iridium, osmium, platinum, and gold. Such elements have extremely low abundances in terrestrial crustal rocks, but their abundances are much higher (100–1000×) in some meteorites. An anomalously high content of siderophile elements (especially iridium) in an impact melt indicates that the melt contains material (perhaps as much as a few percent) derived from the melted and vaporized impactor (e.g., *Palme et al.,* 1979, 1981; *Palme,* 1982; *Schuraytz et al.,* 1996). Such an iridium anomaly, identified in the K/T boundary ejecta layer, provided the first evidence that a large meteorite impact was associated with the K/T extinction (*Alvarez et al.,* 1980). More recently, measurements of osmium isotopic ratios have made it possible to identify even very small amounts (≤0.1 wt%) of the projectile in impact melt units (*Koeberl and Shirey,* 1993; *Koeberl et al.,* 1996c, 1998).

The isotopic systematics of such age-dating systems as Rb-Sr and Sm-Nd can demonstrate that impact melt rocks have been derived from near-surface crustal rocks and not (like most normal igneous rocks) from the deep crust or mantle. Abnormally high $^{87}Sr/^{86}Sr$ ratios are a good indicator of impact melts in relatively young impact structures developed in older crustal rocks; high ratios indicate that the melt was produced by the melting of older and more radiogenic crustal rocks (e.g., *French et al.*, 1970). The study of samarium and neodymium isotopic compositions of the large Sudbury (Canada) Irruptive (*Faggart et al.*, 1985) provided the first strong indication that the entire Irruptive was an impact-melt body derived entirely by melting and mixing of the crustal rocks in which the Sudbury structure is emplaced (see also *Deutsch et al.*, 1995; *Ostermann et al.*, 1996).

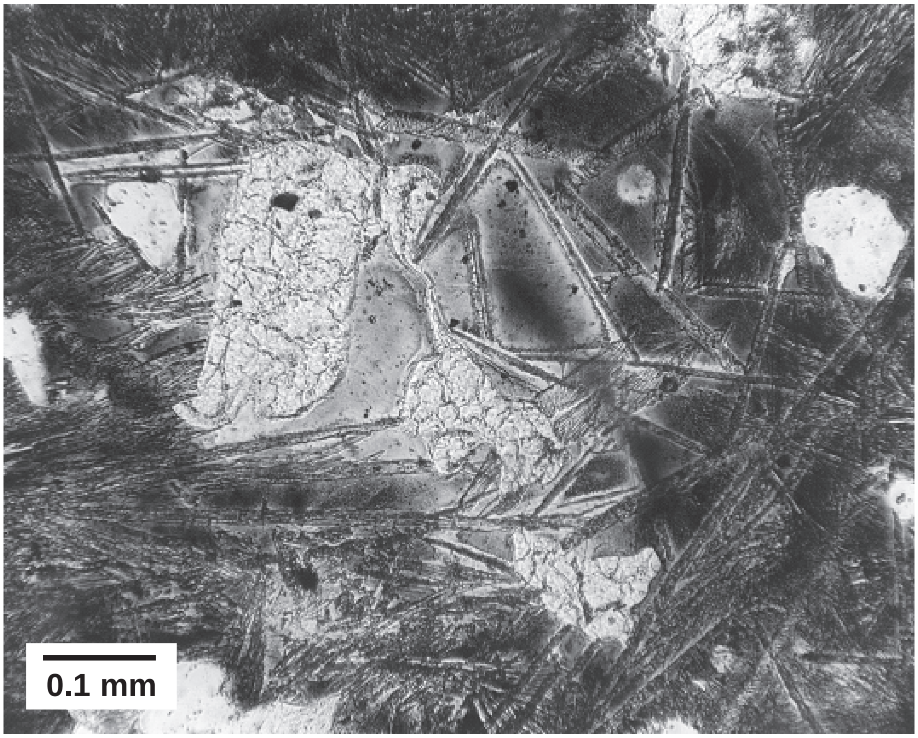

**Fig. 6.21. Impact melt rock; partly crystalline, with lechatelierite.** Finely crystalline impact melt, containing inclusions of quartz glass (*lechatelierite*). Irregular inclusions of clear lechatelierite (light gray) occur in a partly crystalline matrix containing elongate pyroxene quench crystals and clear interstitial brown glass. Contact between lechatelierite and brown matrix glass (central region) is irregular and interpenetrating, indicating that both glasses were originally molten at the same time. The lechatelierite displays a typical crackled (*Ballen*) texture produced by devitrification of the silica glass to silica minerals. The lechatelierite probably originated by shock-melting of original quartz grains, at temperatures above 1700°C, and was incorporated into the more abundant impact melt derived from melting a larger volume of target rock. The presence of small unaltered quartz grains (small scattered white areas) in the impact melt indicates that the lechatelierite did not form by simple in-place thermal melting in a very-high-temperature melt. Sample from a possible dike of impact melt located on the rim of Tenoumer Crater (Mauritania). Specimen courtesy of R. S. Dietz. Sample TM-1-1 (plane-polarized light).