Appendix

CRITERIA FOR RECOGNIZING TERRESTRIAL IMPACT STRUCTURES

(expanded from *Dence,* 1972, pp. 78–79, and other sources)

1. SURFACE FORM AND GEOLOGIC STRUCTURE

Surface Expression and Shape:
- occur in any kind of bedrock (crystalline, sediments, volcanic)
- generally occur as single structures
  - rarely double or small multiple structures
  - larger structures not present as groups
- generally circular
  - elliptical or noncircular in deformed structures
- possible circular depression or definite crater
- also possible circular uplifted region
- may be expressed by physiographic features (e.g., topographic relief, drainage)

Size and Occurrence:
- wide size range, from <1 km to >100 km diameter
- occur in all geological terranes, bedrock (crystalline, sediments, volcanic)
- only **random association** with other geological features

Relatively shallow
- underlain by undeformed regional bedrock
- unusual deformation extends less than one-third apparent diameter

Anomalous feature in regional topography, geology
- **unusual geology** within circular area
- **local deformation:** faulting, brecciation
- **unusual breccias, melt rocks** within structure
  - serve to define structure
  - may be absent (deeply eroded structures)
  - similar breccias rarely present outside structure
    - deposits on or beyond rim
    - in structures with well-defined crater morphology
- **central uplift** of deeper-seated rocks (in larger structures)
  - may form central peak or central ring
  - show definite stratigraphic uplift
  - rocks may contain distinctive **shatter cones***
    - unique conical fractures, striated
    - restored apexes point inward/upward

Vague or ambiguous descriptions in previous literature
- deformation recognized in earlier studies (intense, sudden, localized)
- conventional endogenic mechanisms not adequate
- vague mechanisms proposed
  - unusual volcanic explosions
  - ("cryptoexplosions")

* Indicates unique shock-metamorphic features that provide definite evidence for meteorite impact origin.

CRITERIA FOR RECOGNIZING TERRESTRIAL IMPACT STRUCTURES

1. SURFACE FORM AND GEOLOGIC STRUCTURE (continued)

Brecciation: may be widespread in surface, subsurface samples
- breccia zones in bedrock below crater
  - around rims or in central uplift areas
  - generally in-place monomict breccias
  - rare dike-like bodies of polymict breccia, melt
  - unusual **pseudotachylite** breccias
- polymict breccias and melt rocks
  - may form blanket-like, layered units (crater fill)
  - in central regions (small structures)
  - as annular units around central uplifts (larger structures)

2. GEOPHYSICAL CHARACTERISTICS

Gravity Signature:
- may show circular anomaly following structure
- typically negative (breccias and sedimentary fill)
- may be positive (larger structures; uplift)
- may also be lacking

Magnetic Signature:
- no distinctive typical pattern
- regional anomalies outside structure may be interrupted, subdued, merged within structure
- may be positive anomalies over specific areas
  - melt-bearing rocks, breccias
  - uplifted deep-seated magnetic rocks

Seismic Characteristics:
- lower seismic velocities within structure
  - (from brecciation; presence of sedimentary fill)
- regional stratigraphy interrupted by structure
  - deep seismic reflectors disrupted; chaotic pattern
- regional structure again becomes continuous at relatively shallow depths beneath surface structure
- no evidence of deep roots or connections for structure
  - around margins, presence of concentric shallow inward faults, producing terraced rims

3. ROCK TYPES: GENERAL CHARACTERISTICS

Monomict Breccias:
- abundance, distribution reflect nature of bedrock (homogeneous/heterogeneous)
- areas within bedrock below, around structure
- layers in units that fill structure
- no abnormal deformation in component clasts
- bulk chemical compositions are those of associated local bedrock
- no siderophile-element anomalies (iridium contents, osmium isotopes)

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3. ROCK TYPES: GENERAL CHARACTERISTICS (continued)

Polymict Breccias:

- occurrence: various possible locations:
  - intrusive dike-like bodies in bedrock
  - irregular horizontal layers within structure
    - (may be transitional with melt rocks)
  - along/outside rim of structure **(ejecta)**
    - rare: only in well-preserved structures
- rock fragments: derived from local bedrock only
  - exotic rock types rare to absent
- both melt-bearing and melt-free varieties present
  - melt-bearing: diverse types:
    - melt as discrete fragments; clastic matrix
    - melt-matrix, with bedrock clasts
- melt-bearing types:
  - resemble endogenic volcanic breccias, e.g., ash-flow tuffs, intrusive breccias
  - lack typical volcanic features
    - no phenocrysts, cogenetic volcanic rocks
    - all fragments are broken bedrock clasts
  - may contain distinctive **cored inclusions**
    - (melt rim around bedrock clast)
- breccia units appear deposited all at once
  - no evidence for prolonged volcanic activity
  - no erosional horizons observed between units
- bedrock inclusions often show unusual, distinctive petrographic deformation features
- **bulk chemical compositions** equivalent to compositions of mixed local bedrock types
- **siderophile-element anomalies*** may be present (iridium contents, osmium isotopes)

Melt Rocks:

- occur in diverse locations
  - dike-like bodies in substructure bedrock
  - sill-like units within structure
    - interbedded with breccias
- display range of typical igneous textures
  - features reflect size, cooling rate
- transitional with melt-bearing breccias
- included rock fragments often display unusual petrographic deformation, melting, and recrystallization textures
- **bulk chemical compositions** equivalent to compositions of mixed local bedrock types
- may show **siderophile-element anomalies*** (iridium contents, osmium isotopes)

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4. MICROSCOPIC DEFORMATION AND MELTING FEATURES

Found in a **variety of rock types** and locations in structure
- (1) in-place bedrock in center of structure
  - (rarely preserved or exposed)
  - may be associated with **shatter cones***
- (2) bedrock inclusions in polymict breccias and melt rocks

Not present in rim bedrock or monomict breccia clasts

General characteristics of deformation
- quartzofeldspathic rocks most sensitive, best indicators
- *selective:* each mineral responds in isolation
- *pervasive:* generally affects each mineral grain
- *locally variable:* strong differences in deformation intensity over small areas
  - may be small local glassy veins, pods in rock
- *range of effects:* progressive deformation, melting
  - progressive destruction of original fabric

Fracturing (may not be distinguishable from effects of other geological processes)
- intense, closely spaced parallel sets may be shock-produced
- may be associated with definite shock-deformation features

Unique mineral deformation features (shock-produced)
- **planar deformation features (PDFs)*** in quartz, feldspar
  - multiple sets at distinct orientations
  - may be fresh (continuous) or "decorated" (inclusions)
  - Brazil twins parallel to base (0001)
- **diaplectic glasses***, e.g. *maskelynite* (feldspar)
- **high-pressure mineral phases*:**
  - coesite, stishovite, diamond

Selective mineral melting* of specific minerals in rock
- individual minerals melt; associated minerals not affected
- melted minerals may show incipient flow, vesiculation
- transitions to completely melted rock fragments, heterogeneous glasses

Unusual (high-temperature) melting effects* in rock fragments
- melting, decomposition of normally refractory minerals
  - e.g., **zircon, sphene*** ($T > 1400^{\circ}$–$1700^{\circ}C$)
  - **quartz → lechatelierite*** ($T > 1713^{\circ}C$)
- evidence of rapid quenching, disequilibrium

Unusual **heterogeneous glass fragments** (e.g., *Fladen*)
- mixed rock/mineral fragments in heterogeneous glass
- included rock/mineral clasts show range of unusual deformation, melting effects
- **lechatelierite*** bands, strings (*schlieren*) present in flow-banded glass
- strong indications of disequilibrium, rapid quenching

Deformation, melting textures:
- show modification or complete destruction by later processes (secondary recrystallization, hydrothermal activity, metamorphism)

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