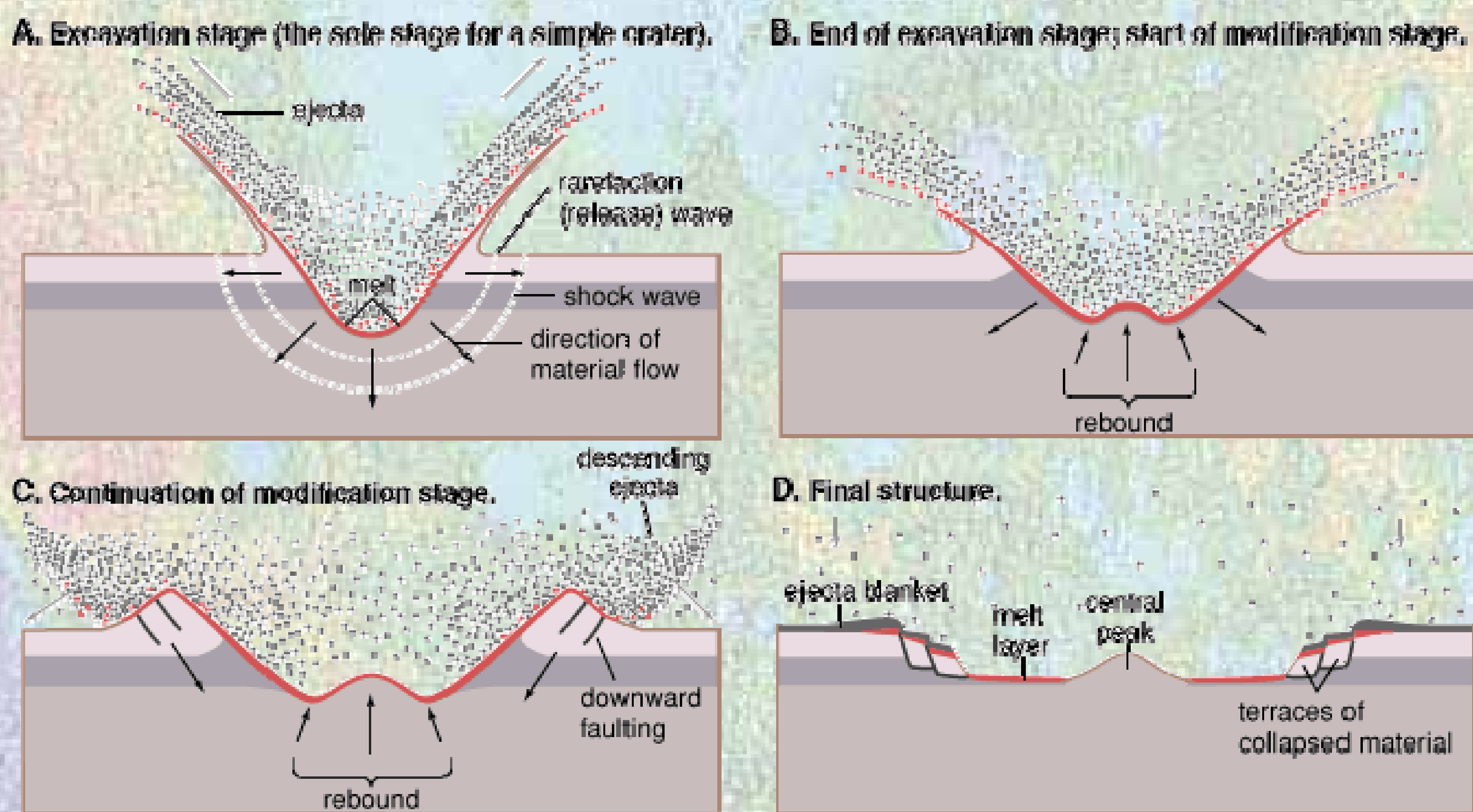
The geophysical signature of impact craters

Stephanie Werner

Observation, geophysical techniques and implications

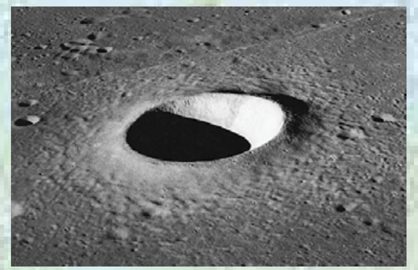
- Gravity Anomalies
- Magnetic Anomalies
- Seismic profiling
- Electrical /Electromagnetic
- Magnetotelluric
- Ground Penetrating Radar
- Radiometric
- …

Crater Formation Process



Observations: Physical

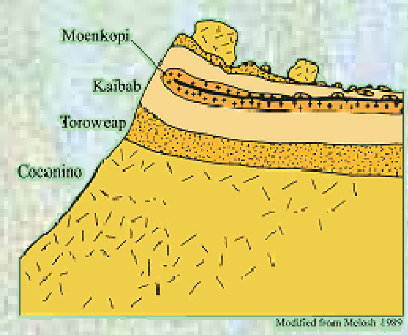
Shape:
circular features



Moltke
(2.7 mi)

Tycho
(53 mi)

Inverted Stratigraphy:
first recognized by Barringer
(only for well preserved craters)



Meteor Crater

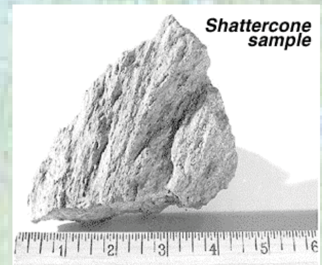
Material displacement:
Solid material broken up and ejected
outside the crater: breccia, tektites

Slide from B. Pierazzo

Observations: Shock Evidence

Shatter cones:

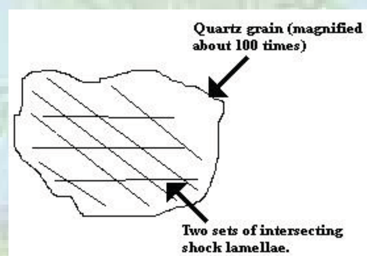
conical fractures with typical markings produced by shock waves

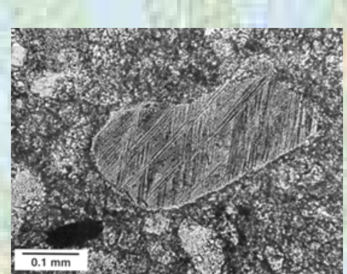


Shocked Material:

shocked quartz

high pressure minerals





Melt Rocks:

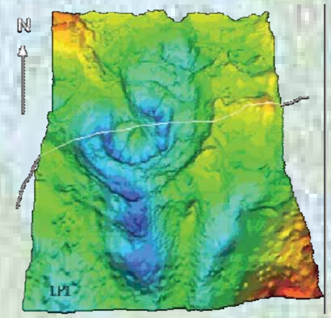
may result from shock and friction

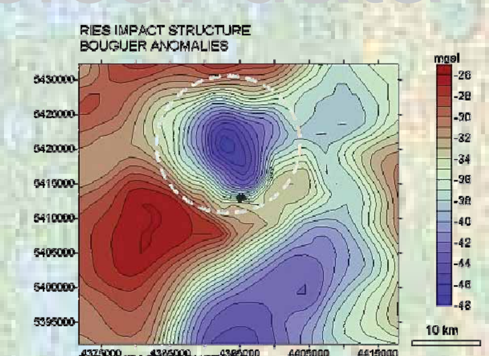
Slide from B. Pierazzo

Observations: Geophysical data

Gravity anomaly:

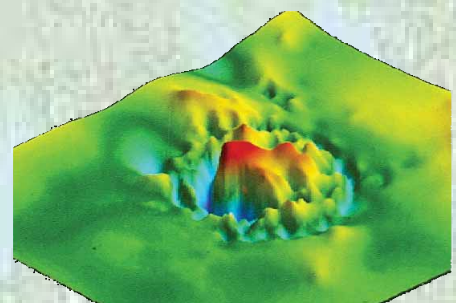
based on density variations of materials

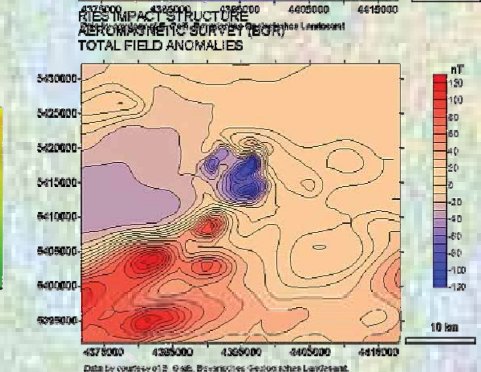




Magnetic:

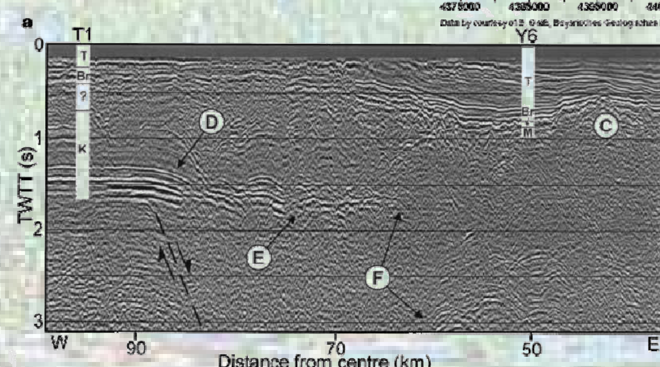
based on *general* variation of magnetic properties of materials





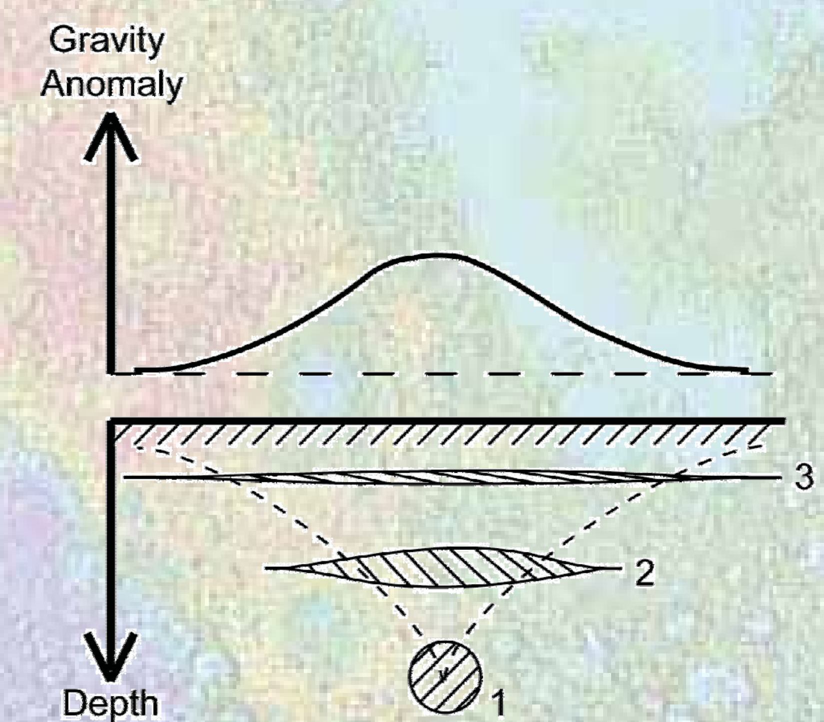
Seismic:

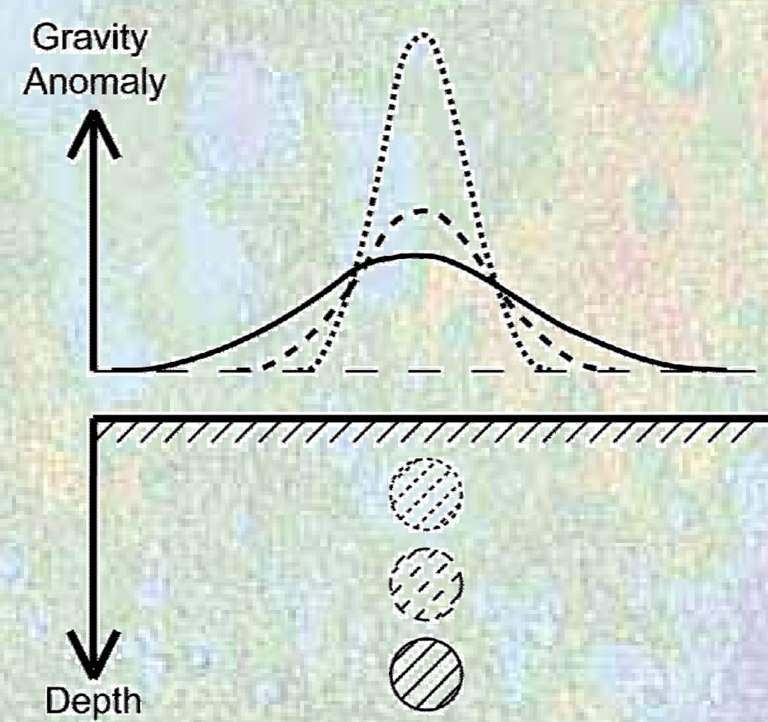
sound waves reflection and refraction from subsurface layers with different characteristics



Slide from B. Pierazzo

Gravity Anomalies



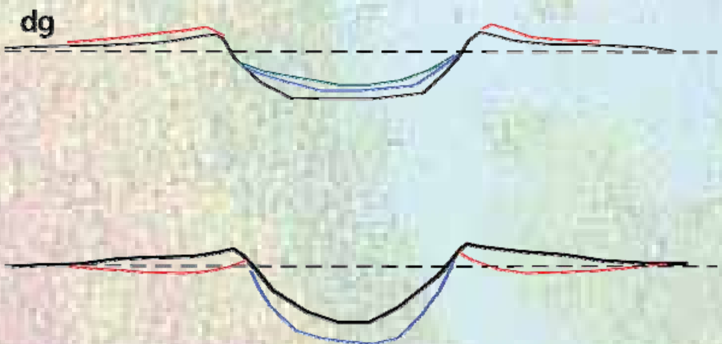


Gravity

- craters are relatively shallow features, but depressions
- associated to brecciation and fracturing, extending to significant depth below the crater floor
- fractured rock is less dense than unaltered rock material
- dependent size and morphology, density contrast and burial depth

➡ circular negative gravity anomaly

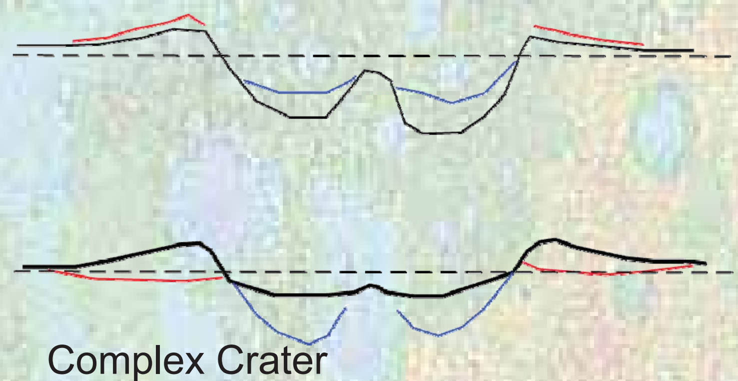
Gravity anomaly: Simple crater

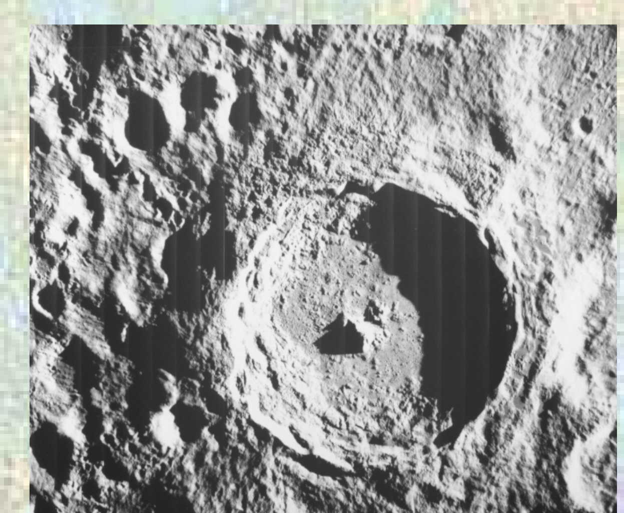


- Negative; unless filled or eroded

Gravity anomaly: Complex Crater

- **fracturing and brecciation of target rock and minerals**
- formation of high-pressure polymorphs
- mineralogic diaplectic change
- uplift of the rim wall
- **formation of allochtonous breccia and melt sheets**



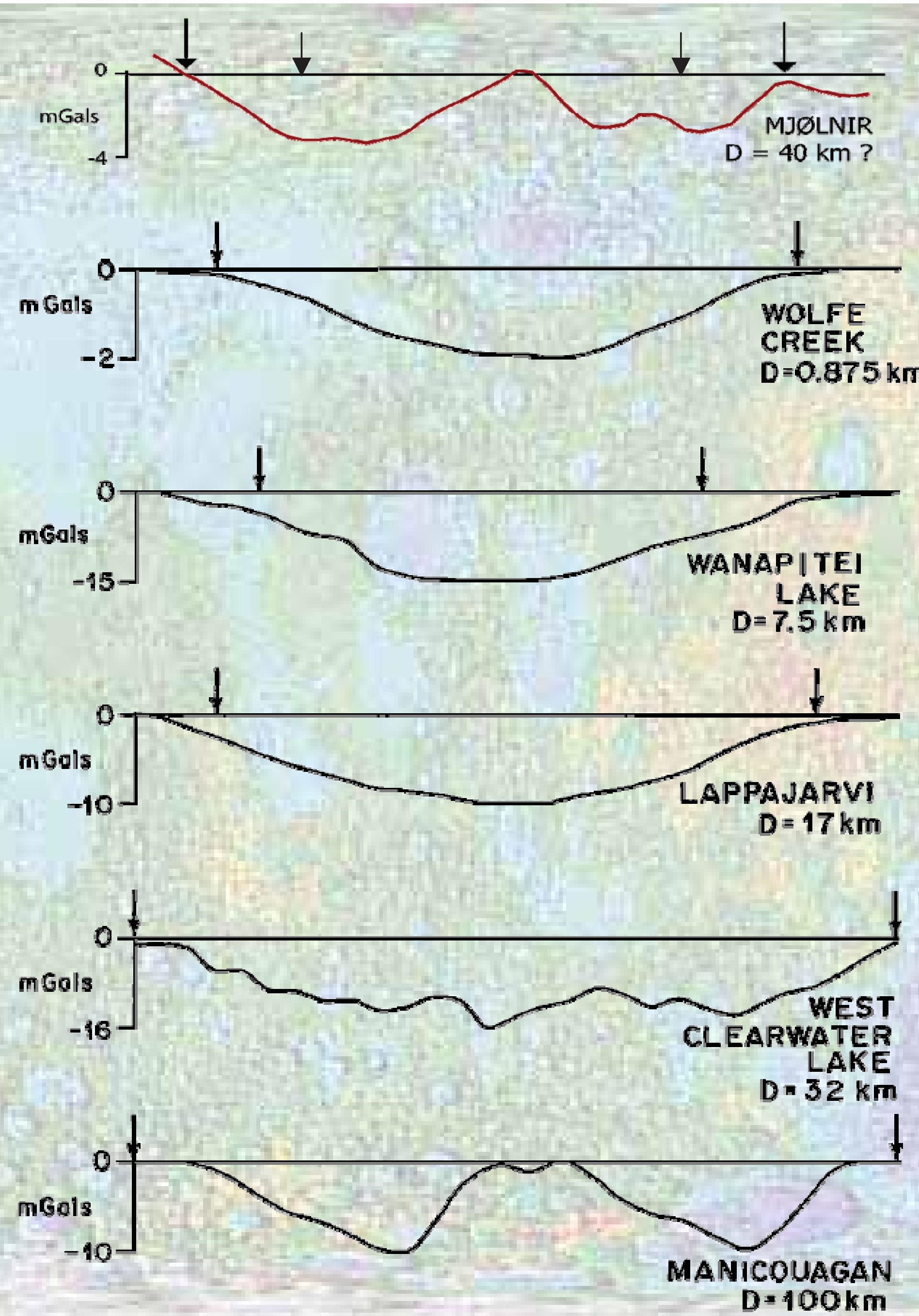


Density Contrast

		kg/m3	km	Ma
Gosses Bluff, Australia	Sedimentary	150	22	142.5 ± 0.5
Mjølnir, Norway	Sedimentary	150	40 (25)	142±6
Brent, Canada	Crystalline	170 - 340	3.8	450± 30
Nicholson Lake, Canada	Crystalline	70 – 140	12.5	~400
Clearwater West, Canada	Crystalline	170	32	290± 20
Holleford, Canada	Crystalline	240	2.35	550 ± 100
Manicouagan, Canada	Crystalline	130	100	212 ± 1
Söderfjärden, Finland	Crystalline	160	6	~550
Average (Crystalline)		177.5		

Pilkington & Grieve 1992

Gravity Signatures



Pilkington & Grieve 1992

Statistics on gravity anomalies

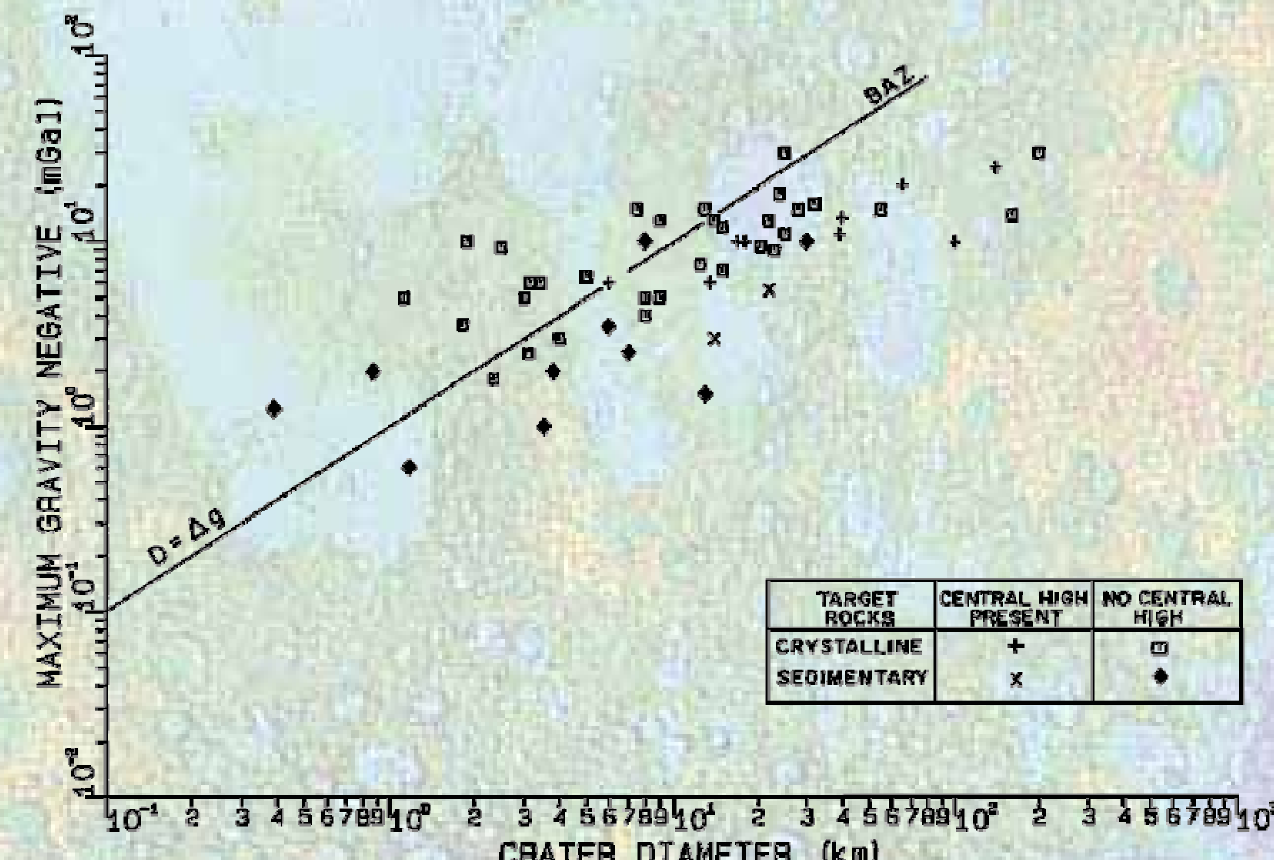
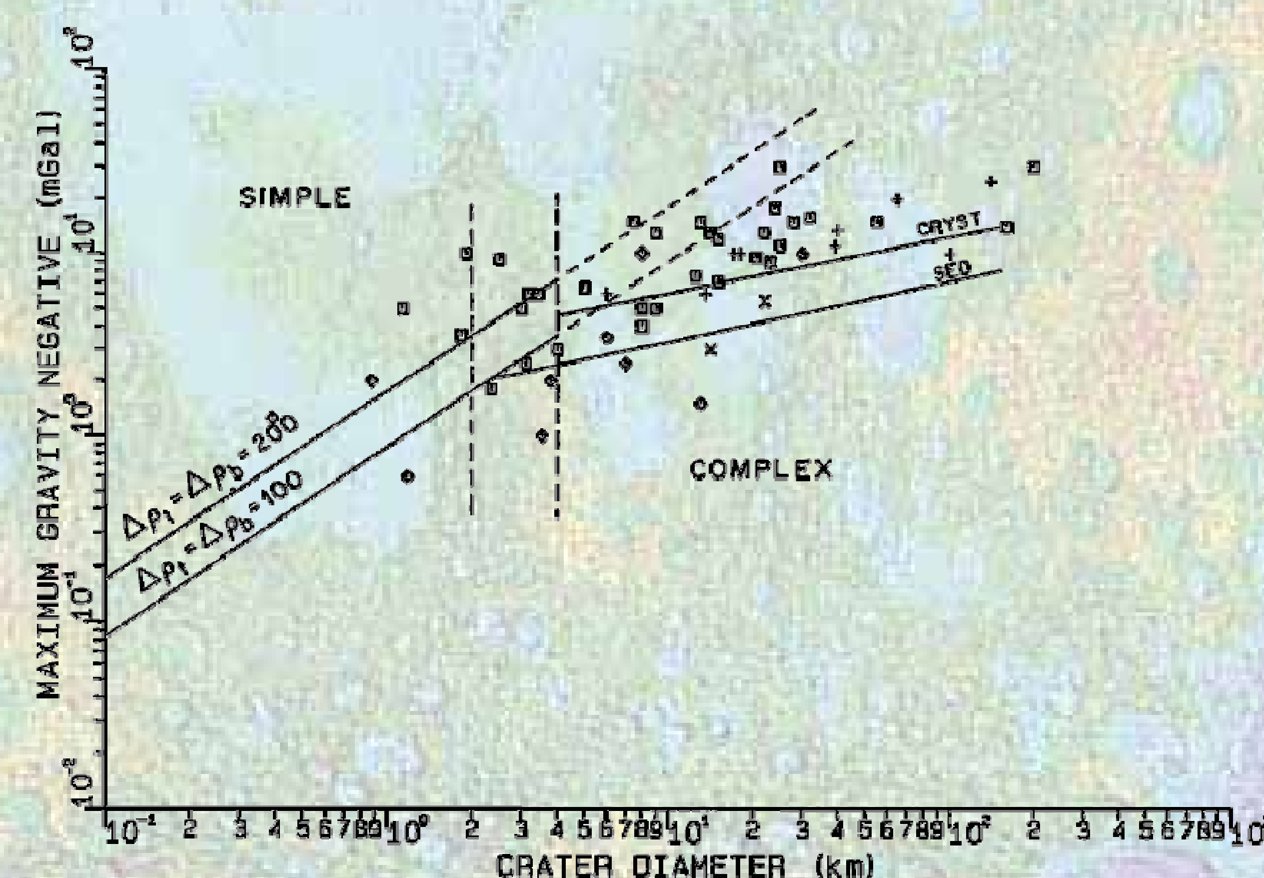


Figure 4. Variation in the maximum negative gravity anomaly with crater diameter. Line marked BAZ shows the variation predicted by the simple hemispherical crater model of *Basilevsky et al.* [1983].

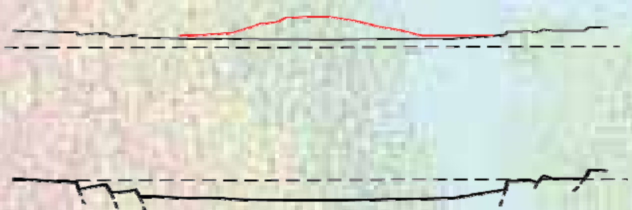
Pilkington & Grieve 1992

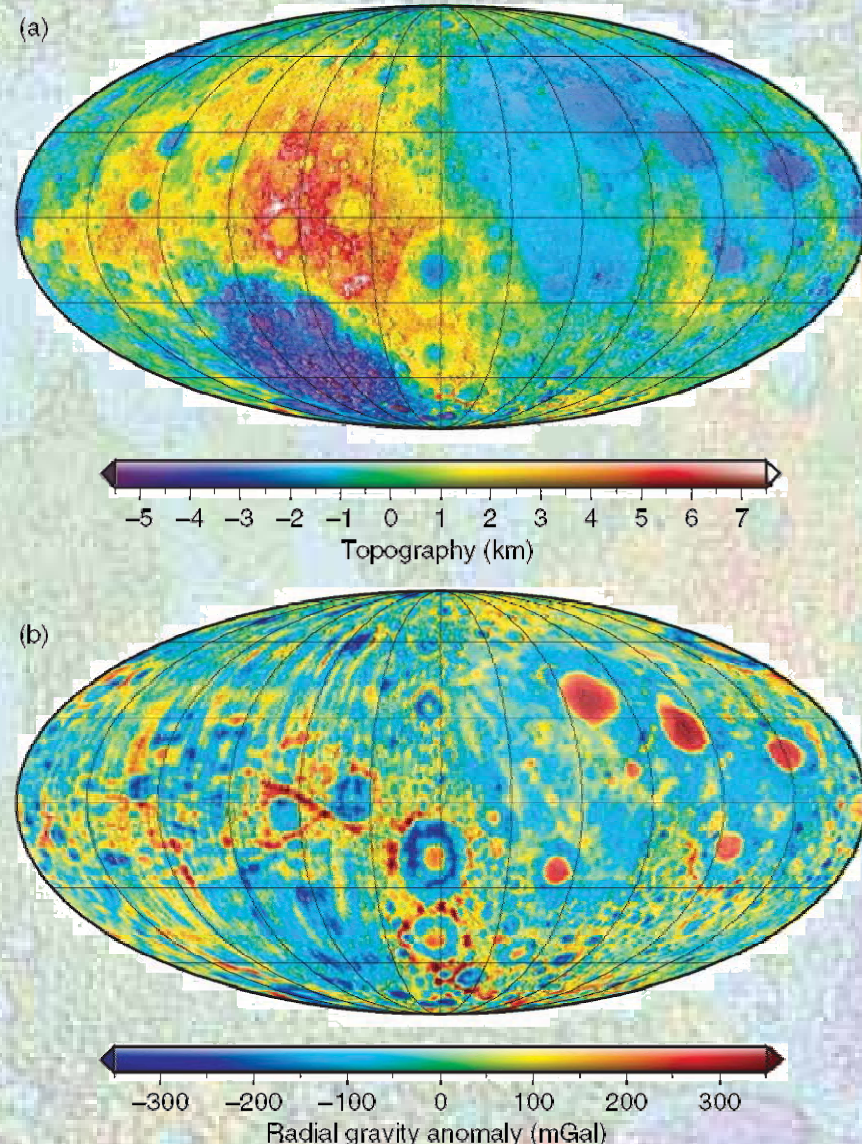
Modelled …



Pilkington & Grieve 1992

Mascon





Wieczorek 2007

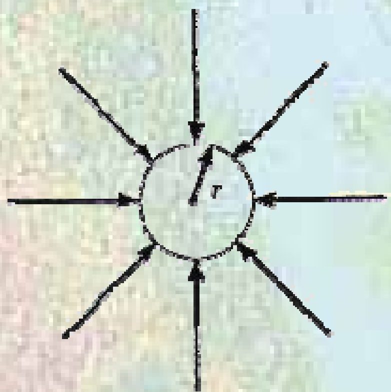
Typical Densities

Table 8.1 Densities of some rock types

	Density (Mg/m³)
Unconsolidated	
clay	1.5–2.6*
sand, dry	1.4–1.65
sand, saturated	1.9–2.1
Sediments	
chalk	1.9–2.5
coal, anthracite	1.3–1.8
coal, lignite	1.1–1.5
dolomite	2.3–2.9
limestone	2.0–2.7
salt	2.1–2.6
sandstone	2.0–2.6
shale	2.0–2.7
Igneous and metamorphic	
andesite	2.4–2.8
basalt	2.7–3.0
gneiss	2.6–3.0
granite	2.5–2.8
peridotite	2.8–3.2
quarzite	2.6–2.7
slate	2.6–2.8
Minerals and ores	
barite	4.3–4.7
chalcopyrite	4.1–4.3
galena	7.4–7.6
haematite ore	4.9–5.3
magnetite ore	4.9–5.3
pyrite	4.9–5.2
sphalerite	3.5–4.0
Other	
oil	0.6–0.9
water	1.0–1.05

*The ranges of values (taken from a variety of sources) are approximate. Densities depend partly on whether the rock is weathered and the degree of its porosity.

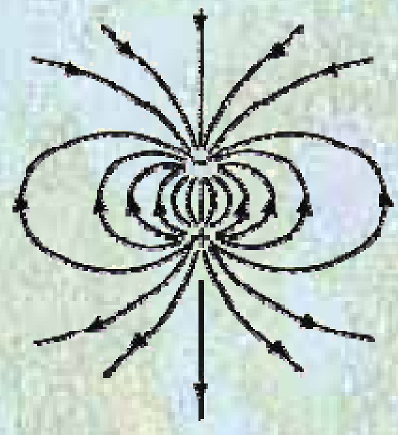
Potential fields

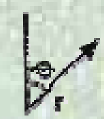


monopole

$$g = \frac{Gm}{r^2}$$

m = mass





dipole

$$B_r = \frac{2m\cos\theta}{r^3}$$

$$B_\theta = \frac{m\sin\theta}{r^3}$$

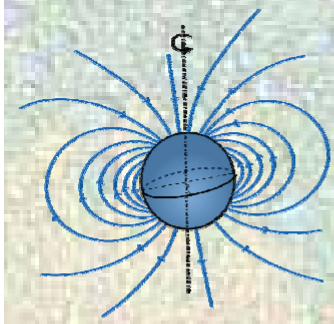
m = dipole moment

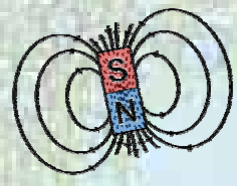
Gravity Field

Magnetic Field

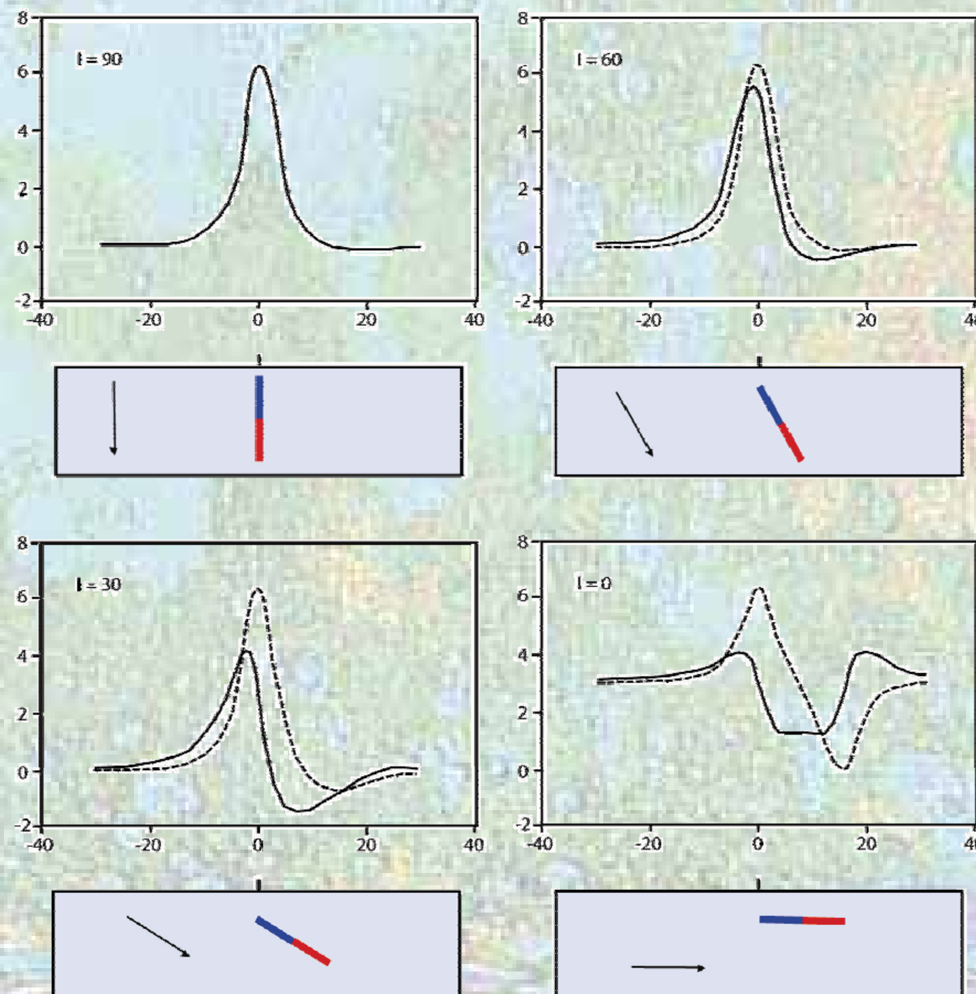
Gravity – Magnetic Field

monopolar	dipolar
attractive (+ or -)	attractive and repulsive (+ AND -)
$1/R^2$ dependency	$1/R^3$ dependency
density variations	variation of magnetic susceptibility
reflects a bulk rock property	reflects presence of trace elements
Source depth is very non-unique	source depth within 10-20% accuracy
stable	time dependent





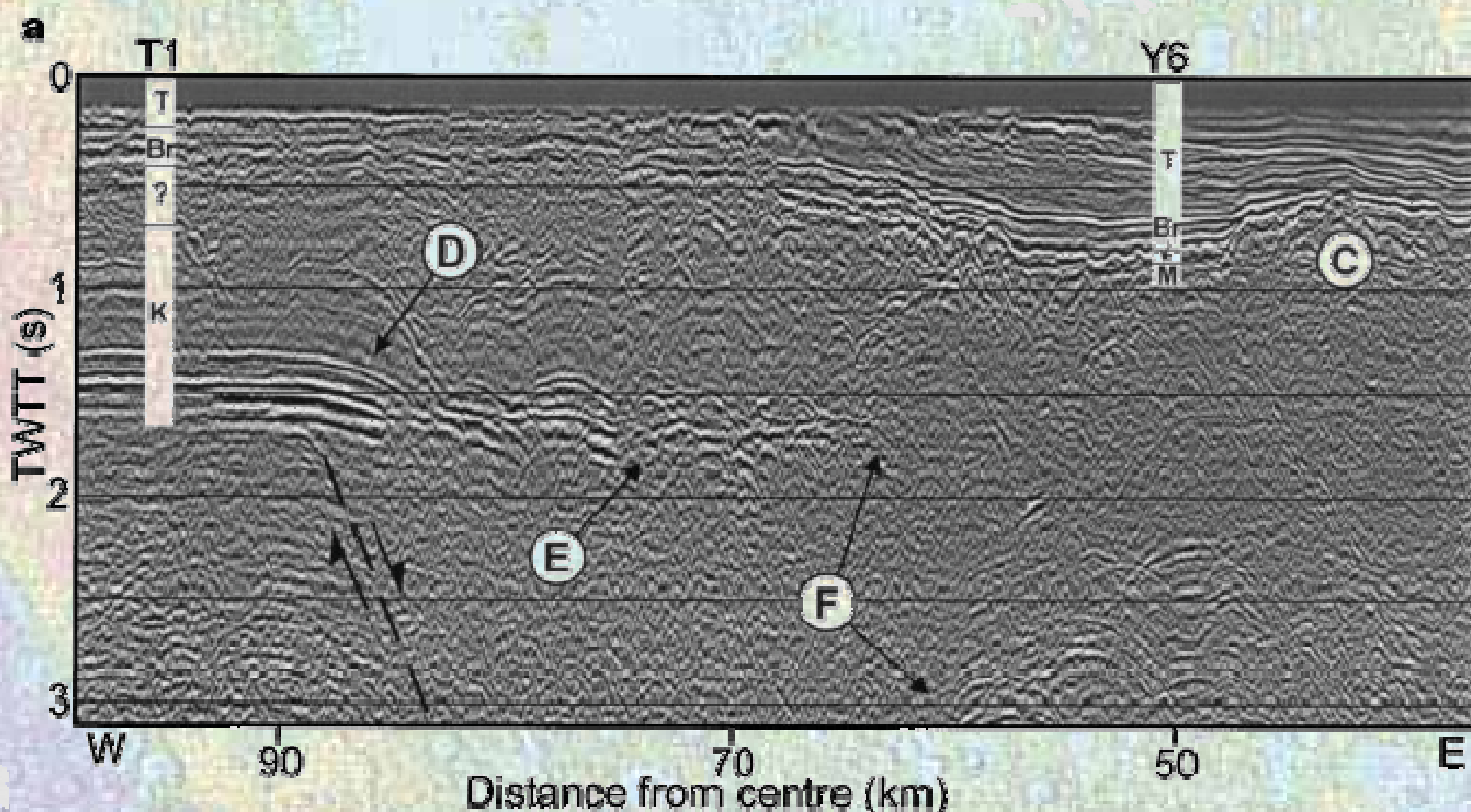
Magnetic Anomalies



Magnetic anomalies

- more complicated than gravity
- no specific signature, but
  - anomalous low or random signature interrupt the regional magnetic pattern (fragmentation and mixing of target rock)
  - strong local magnetic anomaly (melt or uplift)
  - circular
  - if associated to melt, it could be used for palaeomagnetic dating

Seismic Reflection or Refraction



Sound waves (pulses) are sent downward. They are reflected or refracted by layers with different properties in the crust. Different materials have very different sound speeds

Seismic studies

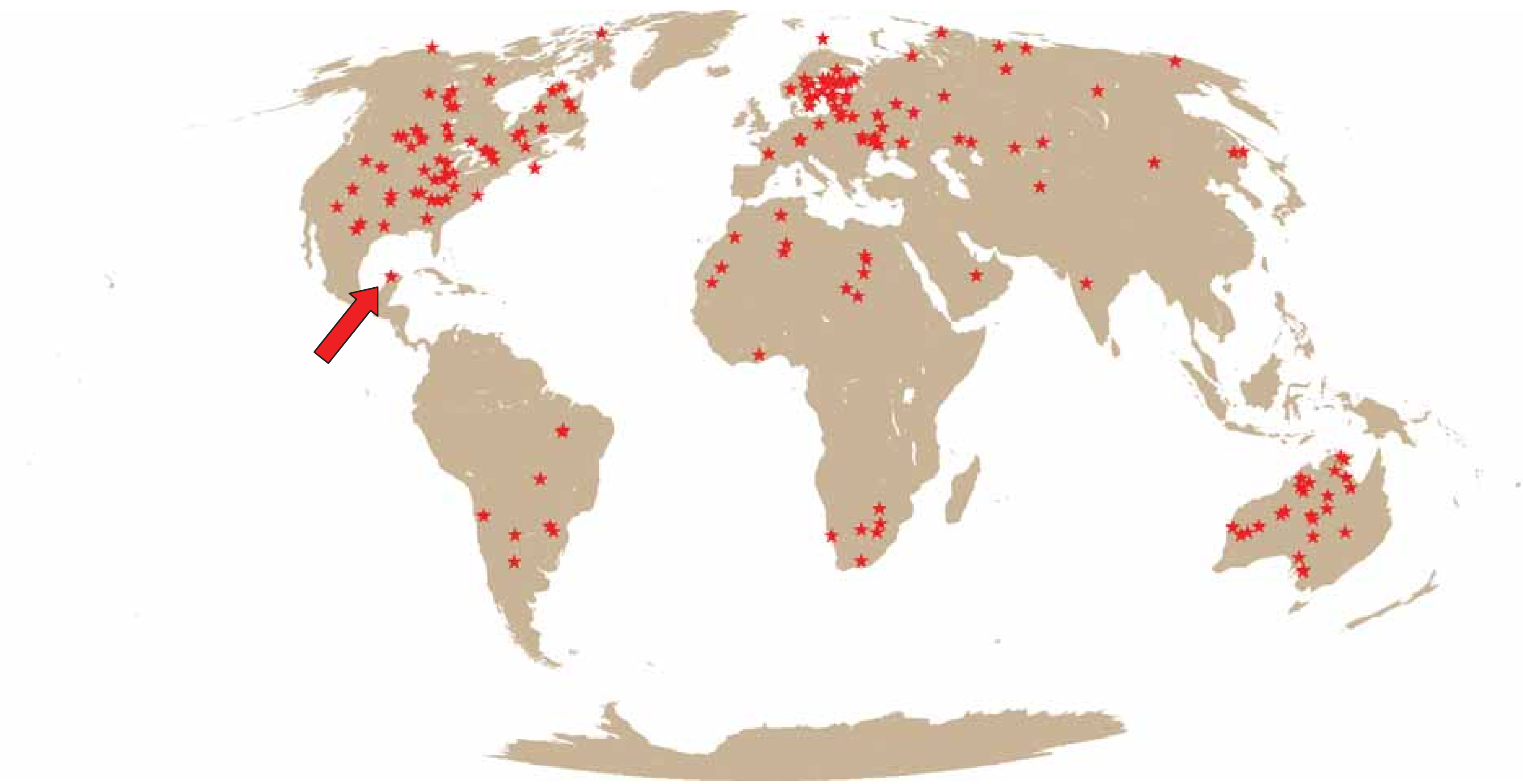
- refraction and reflection
- reveal subsurface deformation, distinctive for impact structures
  - modest downward and inward displacement of rocks along the edges
  - structural disruption with no coherent seismic reflectors, (roughly corresponding to the transient cavity)
  - presence of reflectors in the central zone at greater depth, is evidence that the structure is shallow and not connected with roots the lower crust or mantle

  - essential when buried under younger sediments or water

Electrical Methods

- resistivity variations due impact related target modification
  - impact induced increased porosity and fluid content (low)
  - uplifted material (high)
  - extends farther than the rim

Global Crater Distribution

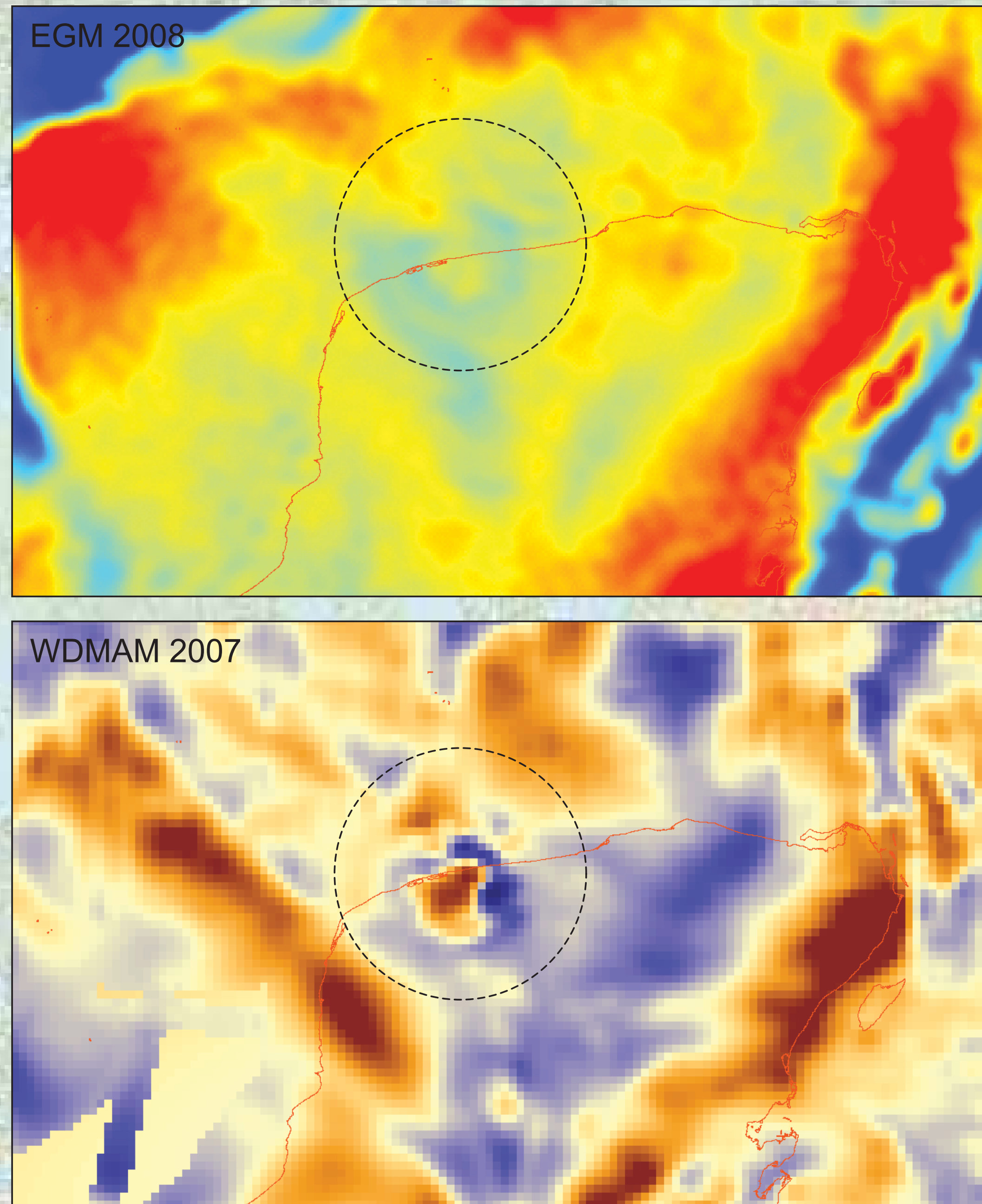


http://www.unb.ca/passc/ImpactDatabase/

Chicxulub

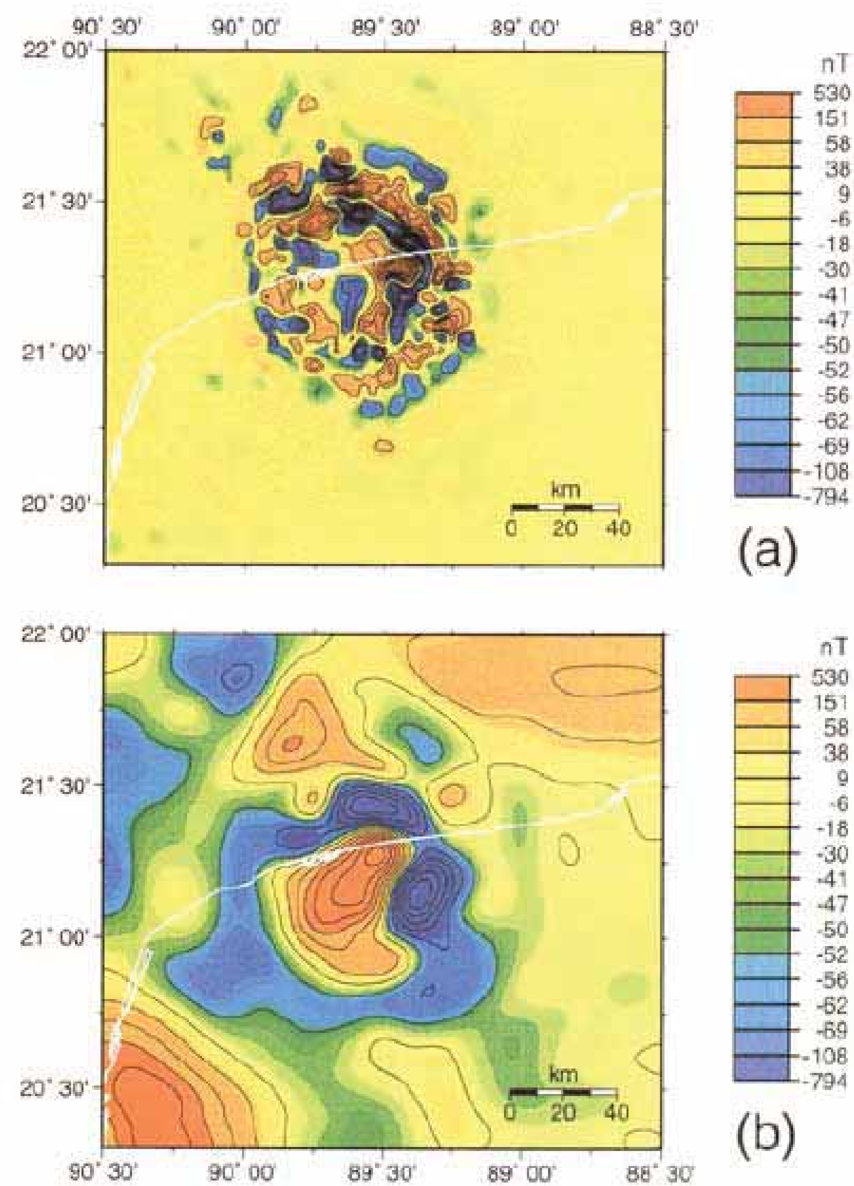
21°20'N 89°30'W
170 km 64.98 ± 0.05 Ma

Chicxulub



Chicxulub

filtered magnetic anomalies

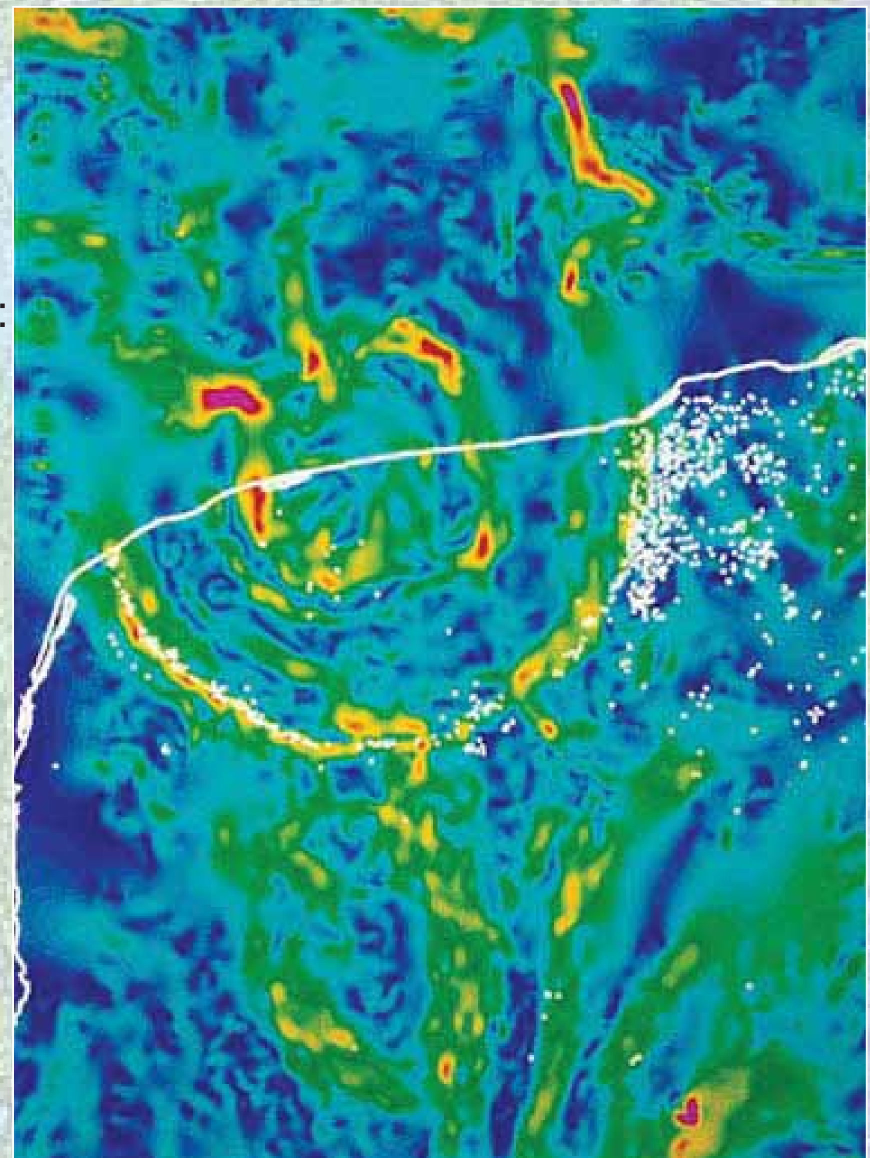


Pilkington & Hildebrand 2000

Chicxulub

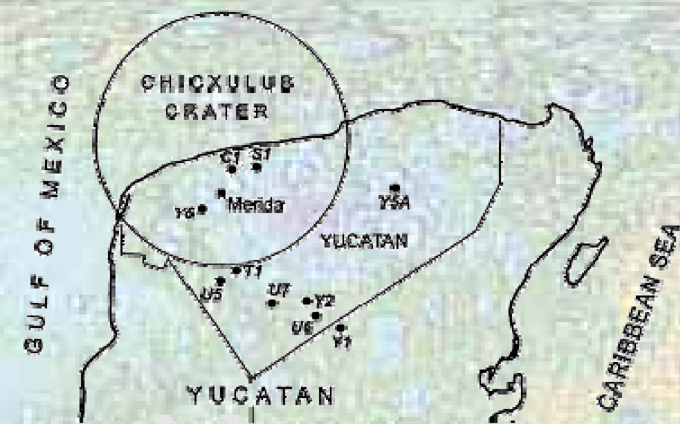
Bouguer gravity horizontal gradients:
highlights lateral density contrasts
and suppresses regional anomalies

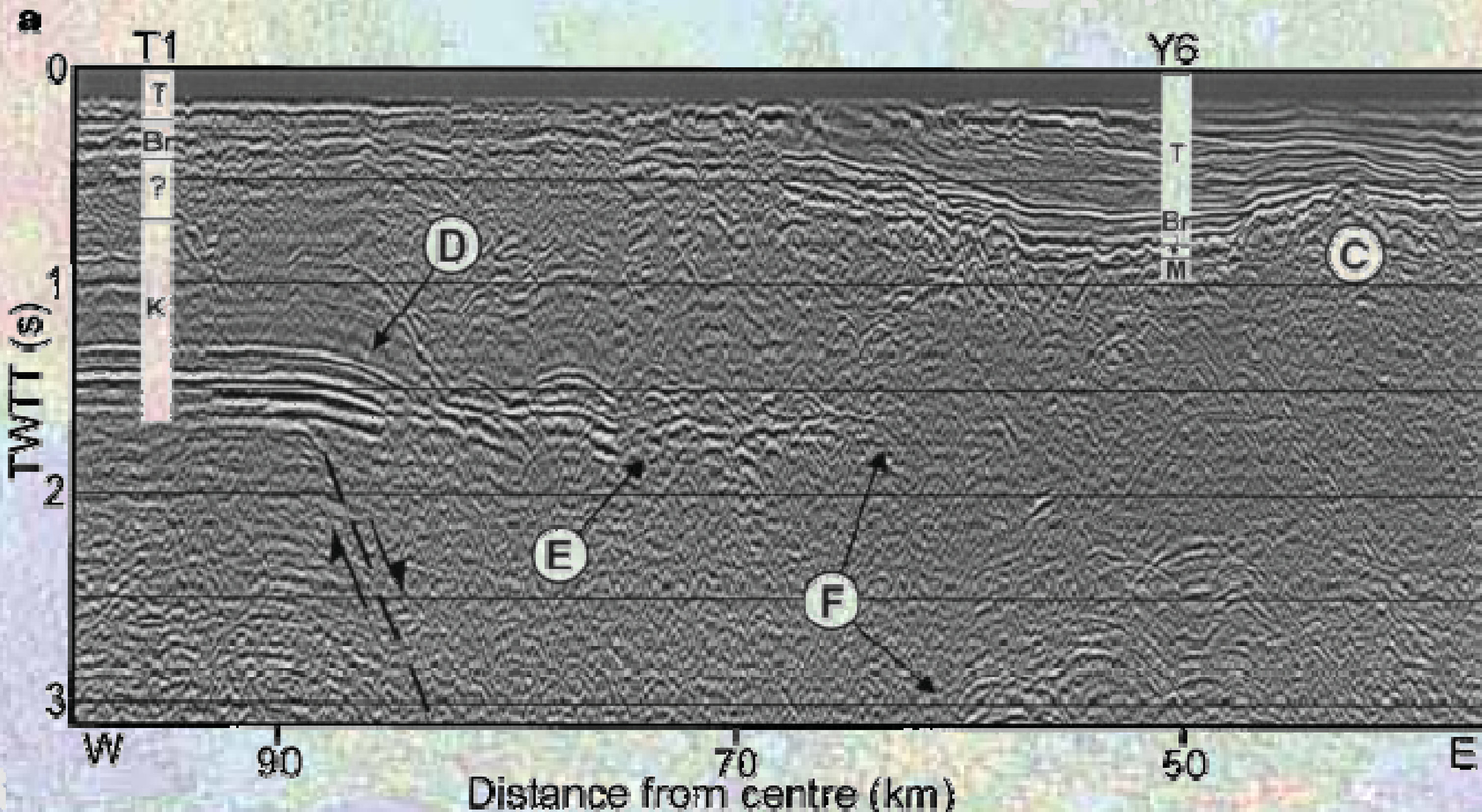
Cenote distribution



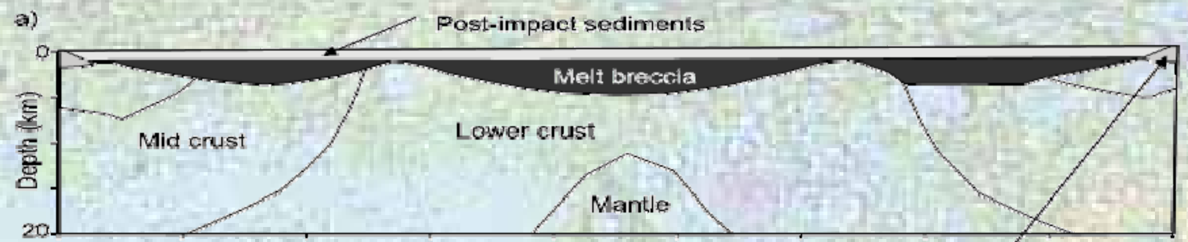
Hildebrand et al. 1995

Chicxulub

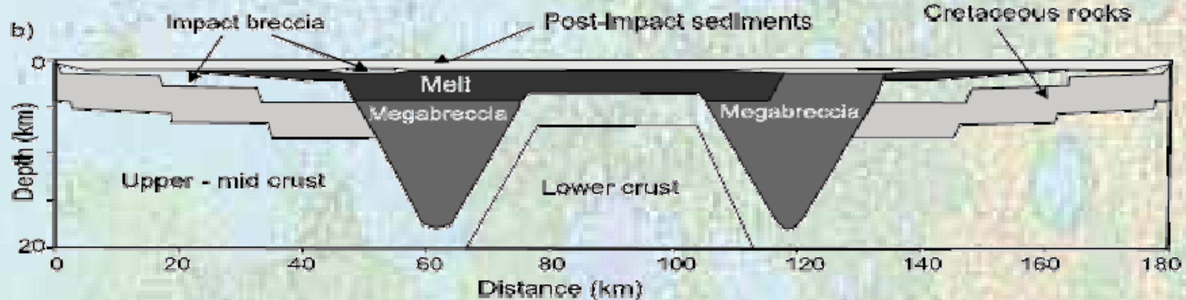

CHICXULUB CRATER
GULF OF MEXICO
Merida
YUCATAN
YUCATAN
CARIBBEAN SEA


a
T1
Y6
T
Br
?
K
T
Br
M
D
C
E
F
TWTT (s)
0
1
2
3
W
90
70
50
E
Distance from centre (km)

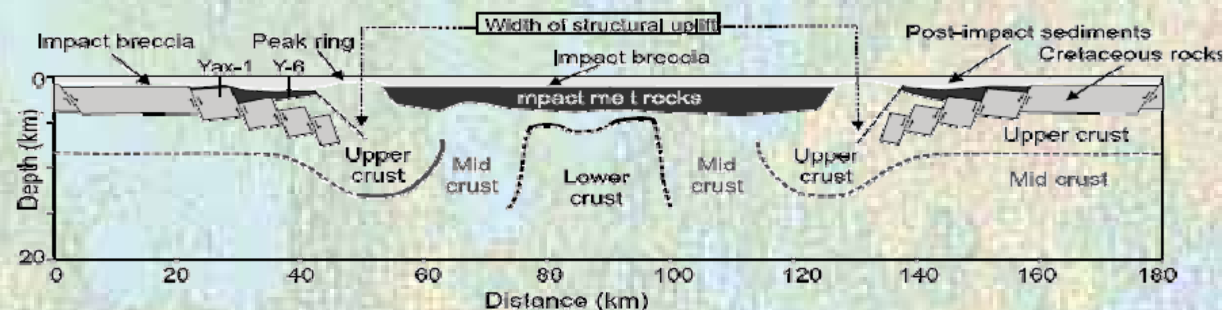
Sharpton et al. 1996



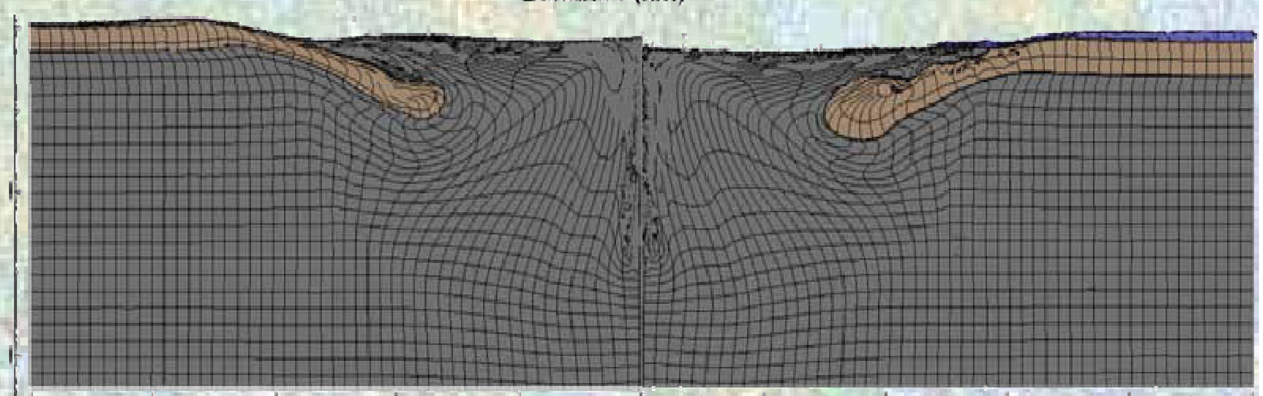
Hildebrand et al. 1998



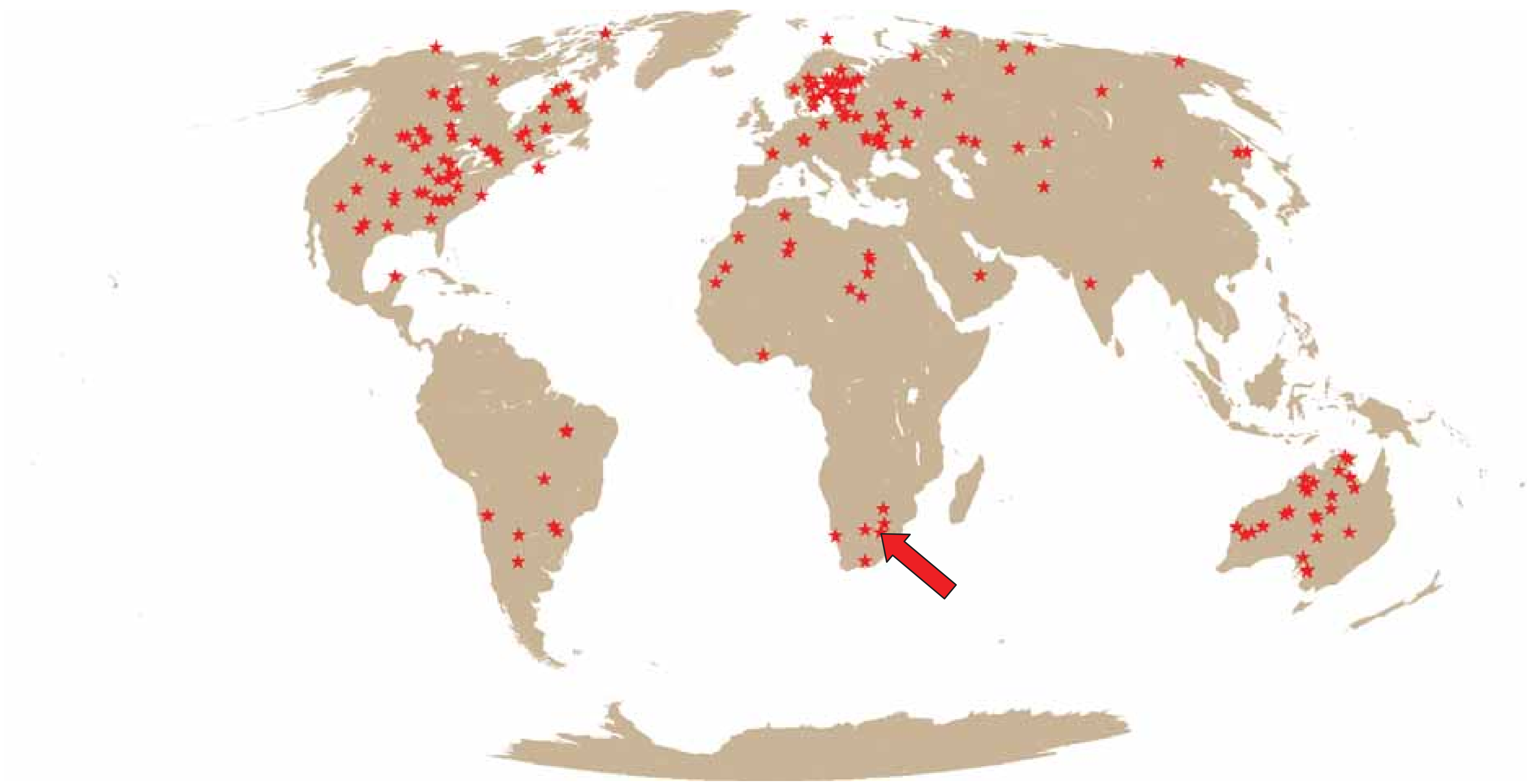
Vermeesch & Morgan 2008



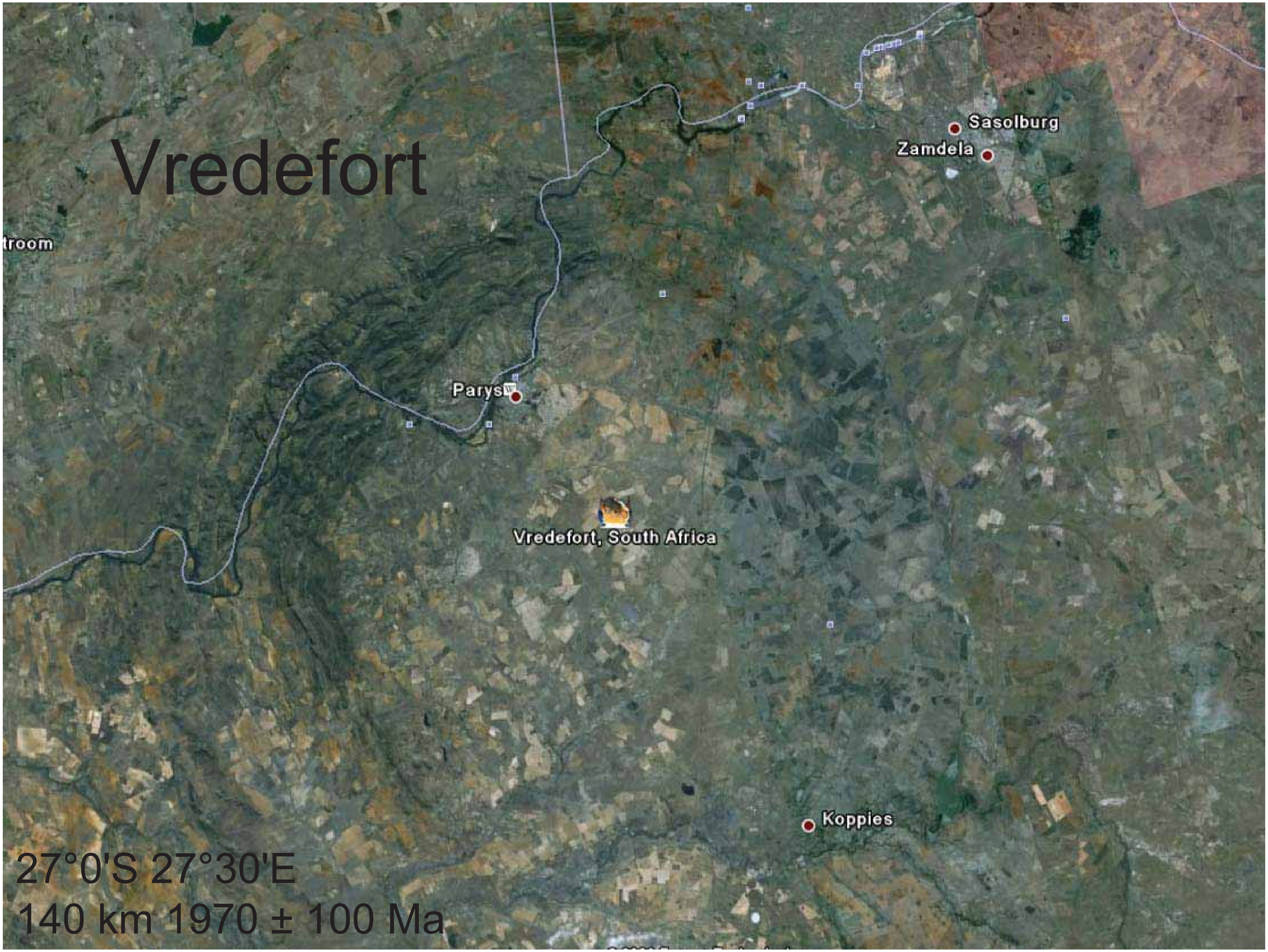
Collins et al. 2008



Global Crater Distribution



http://www.unb.ca/passc/ImpactDatabase/


Vredefort
Sasolburg
Zamdela
troom
Parys
Vredefort, South Africa
Koppies
27°0'S 27°30'E
140 km 1970 ± 100 Ma

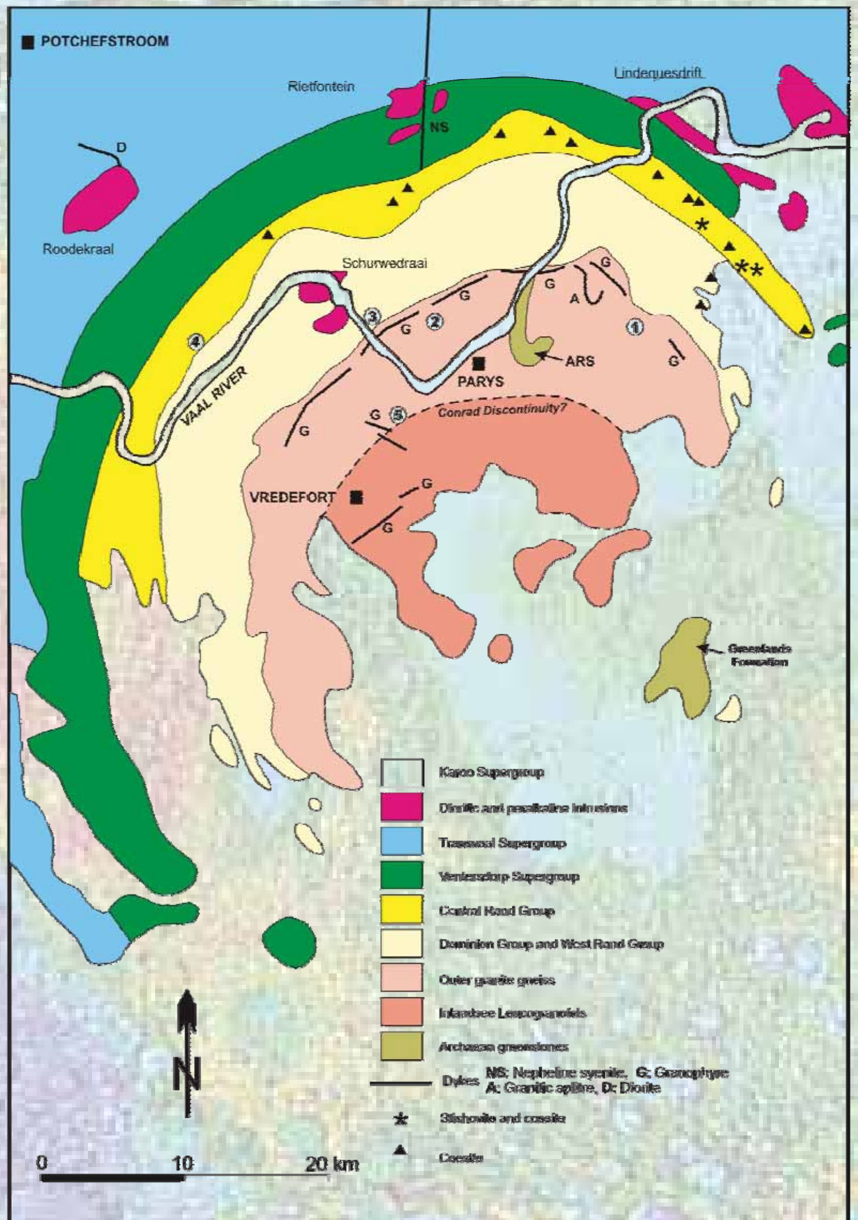
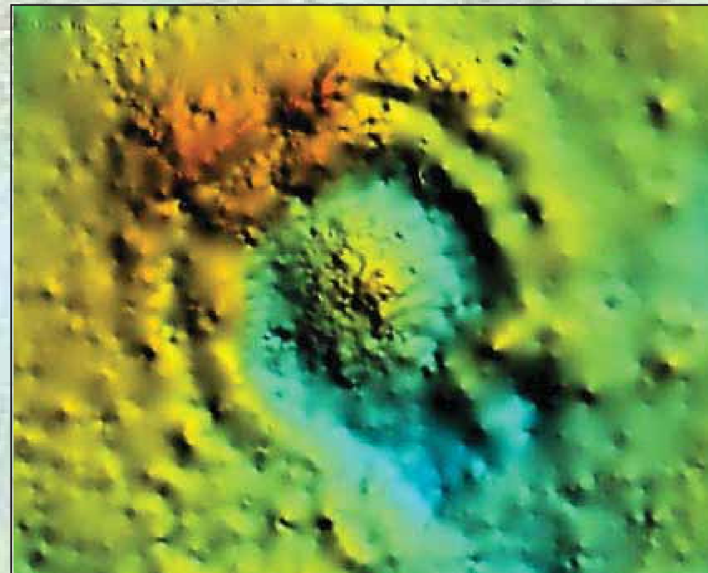
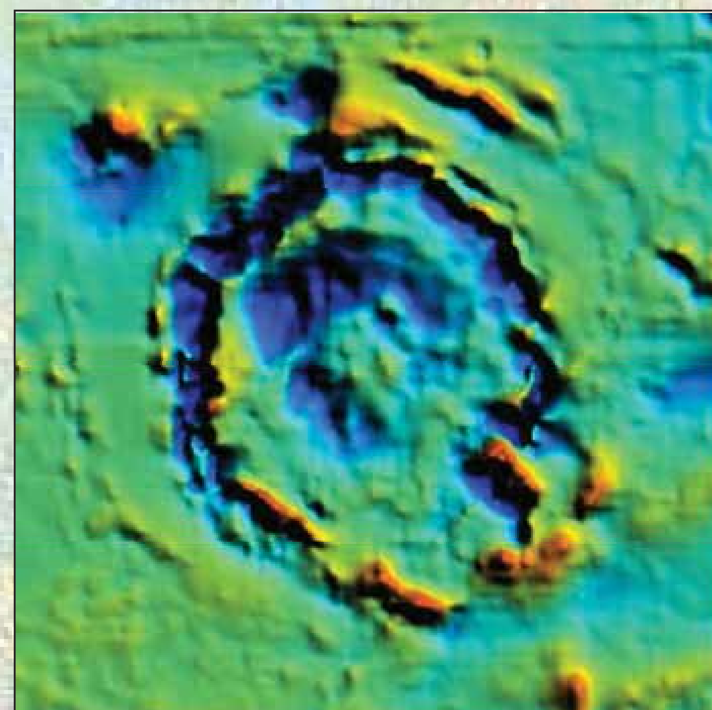
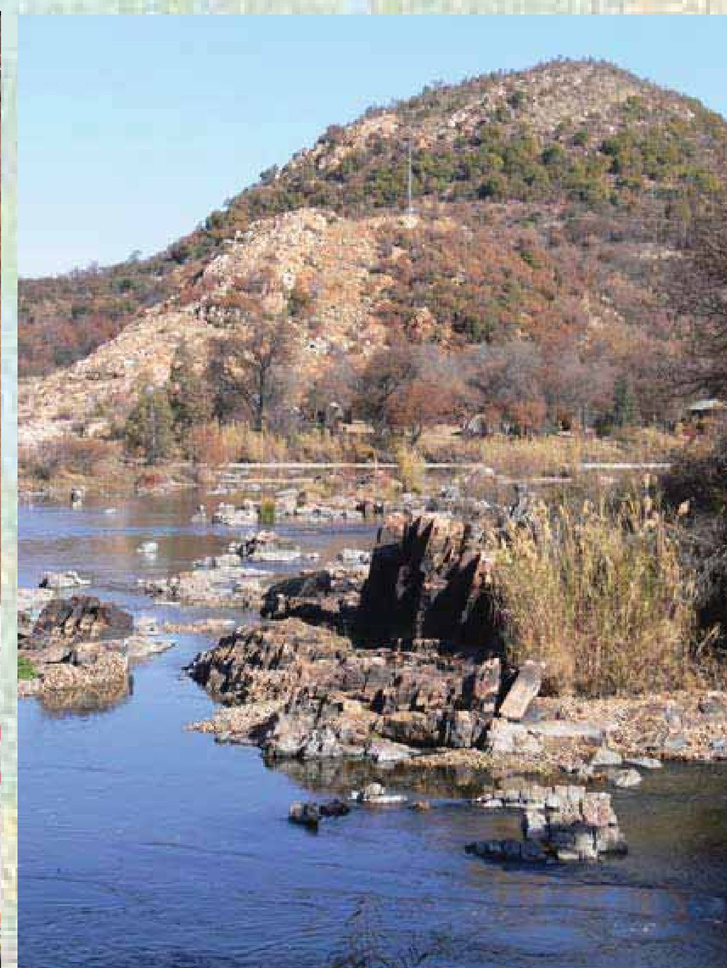


Fig. 3. Geological map of the Vredefort impact structure, modified from Gibson and Reimold (2001). ARS = Anna's Rust Sheet.

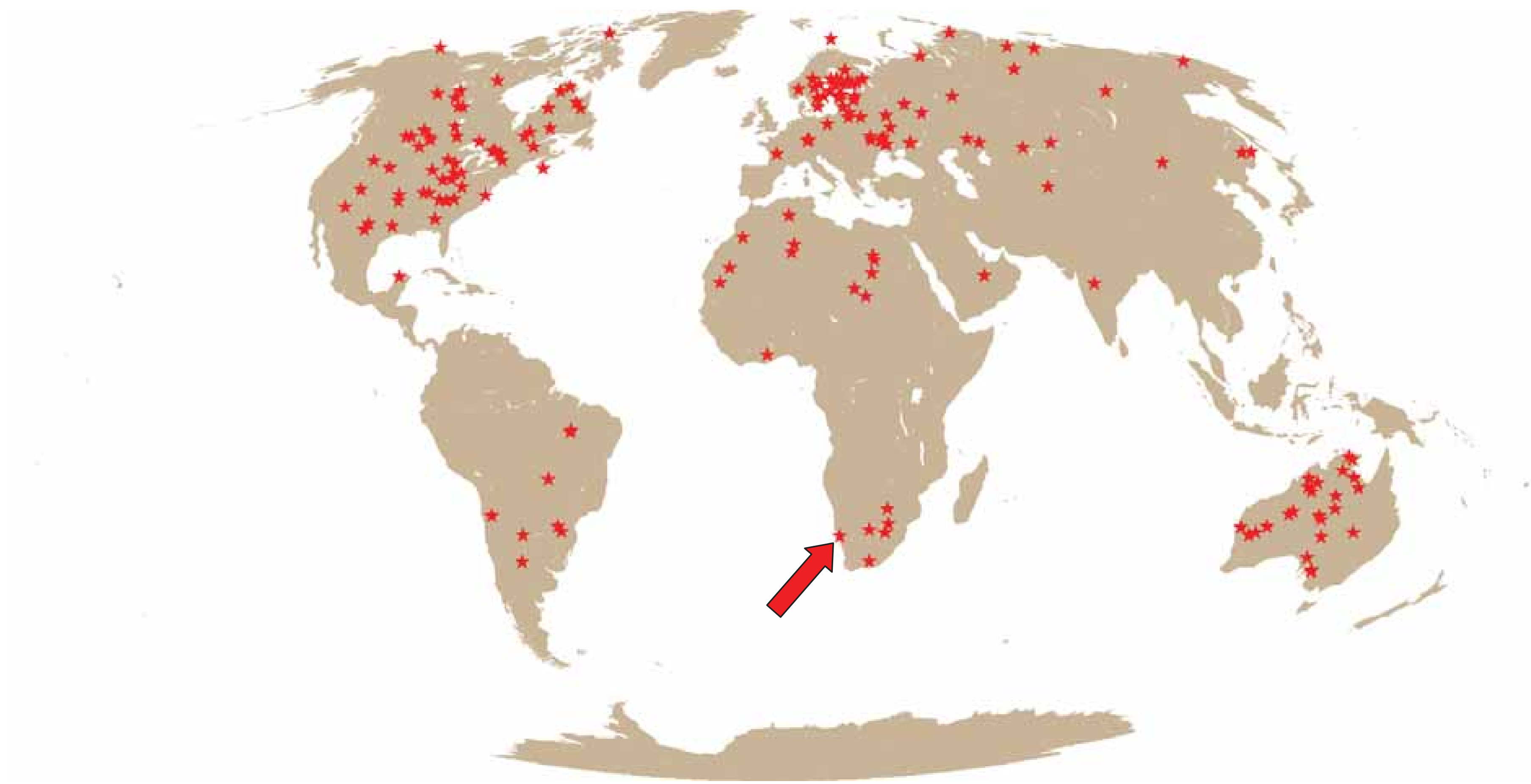




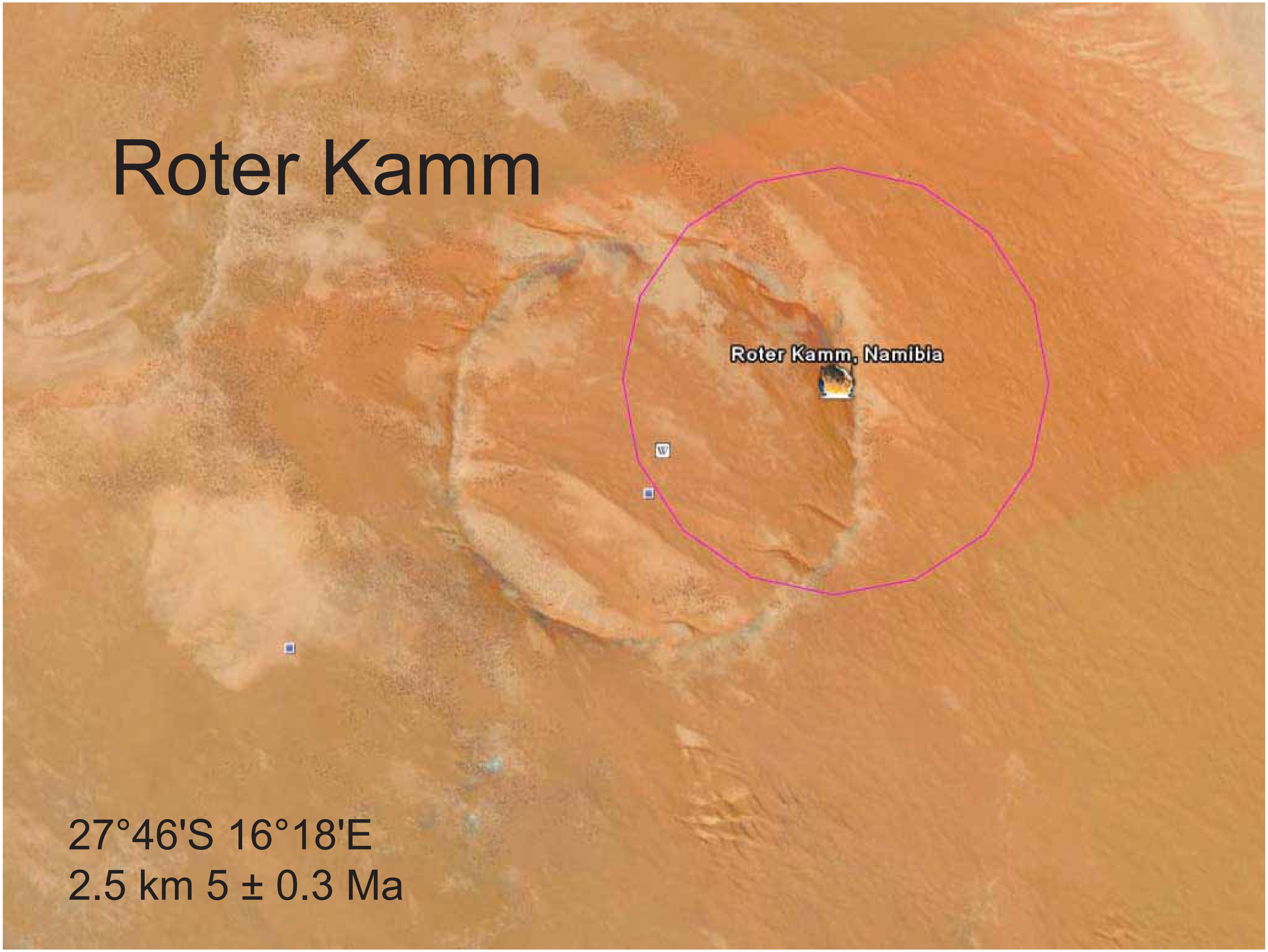
Geological / Structural Interpretation



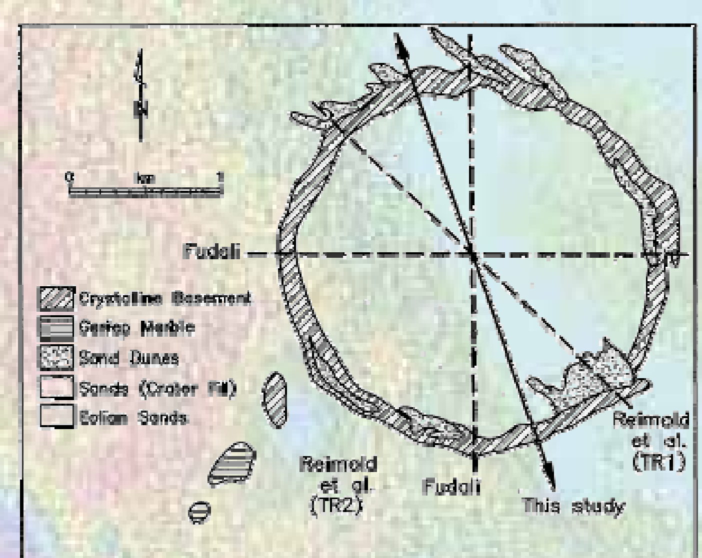
Global Crater Distribution

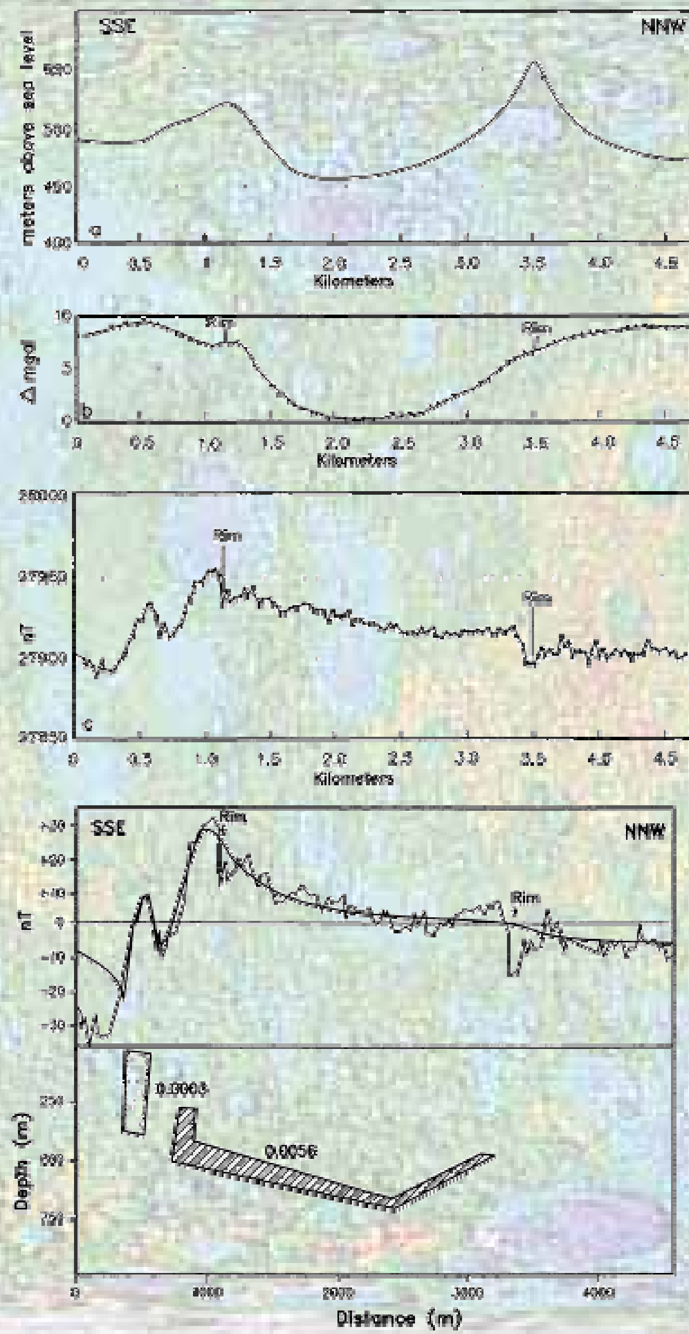


http://www.unb.ca/passc/ImpactDatabase/


Roter Kamm
Roter Kamm, Namibia
27°46'S 16°18'E
2.5 km 5 ± 0.3 Ma

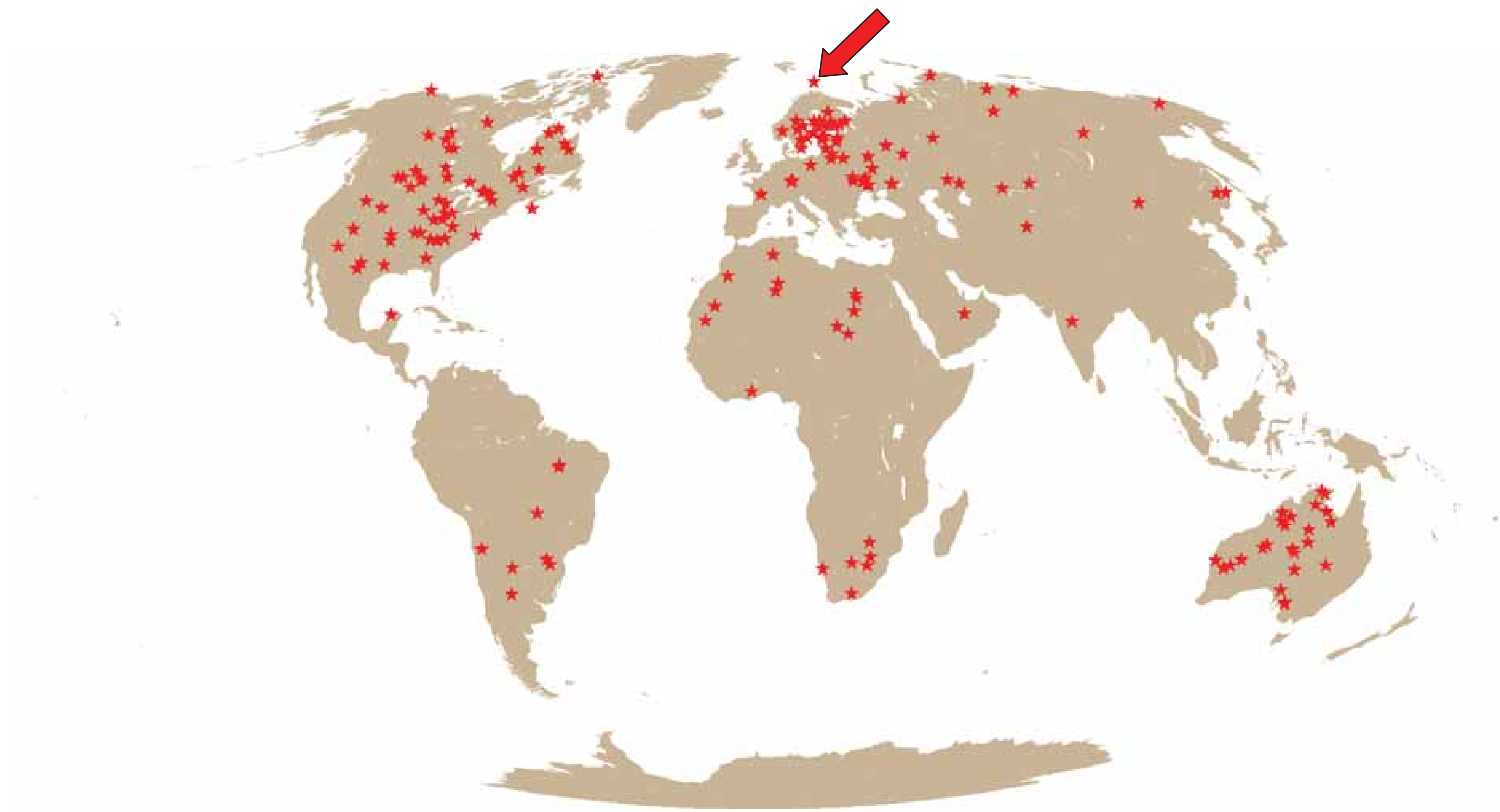
Roter Kamm





Brandt et al. 1998

Global Crater Distribution



http://www.unb.ca/passc/ImpactDatabase/


Mjølnir
Svalbard
Longyearbyen
Kara, Russia
Mjølnir, Norway
Jan Mayen
Saarijärvi, Finland
Suavjärvi, Russia
Google Earth & Earth Impact Database

Morphology

- 40 km in diameter
- 8-km wide central uplift,
  4-km wide annual trough
  and a 12-km wide outer zone

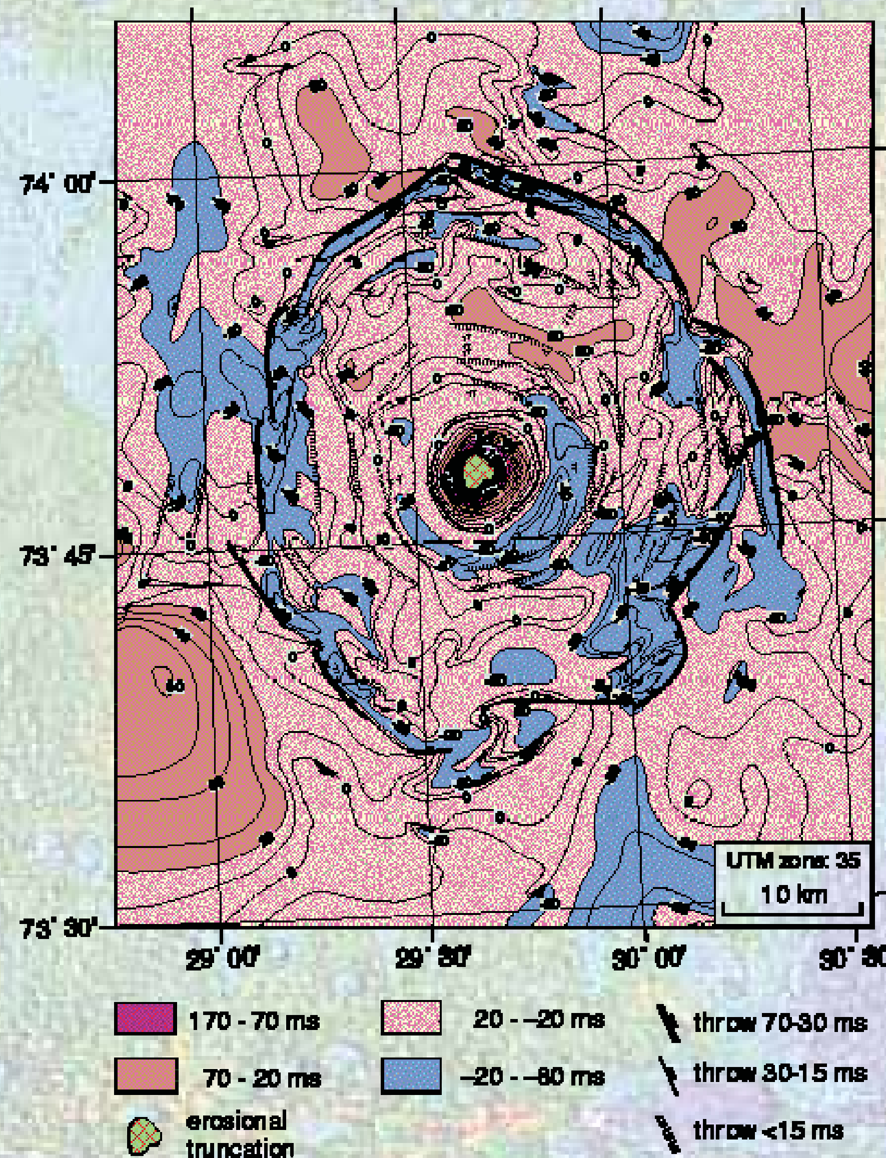
  Gudlaugsson, 1993

- apparent depth 30-70 m

  Tsikalas et al. 1998

- Volgian-Ryazanian;142±6 Ma

  Dypvik et al. 1996; Smelror et al. 2001

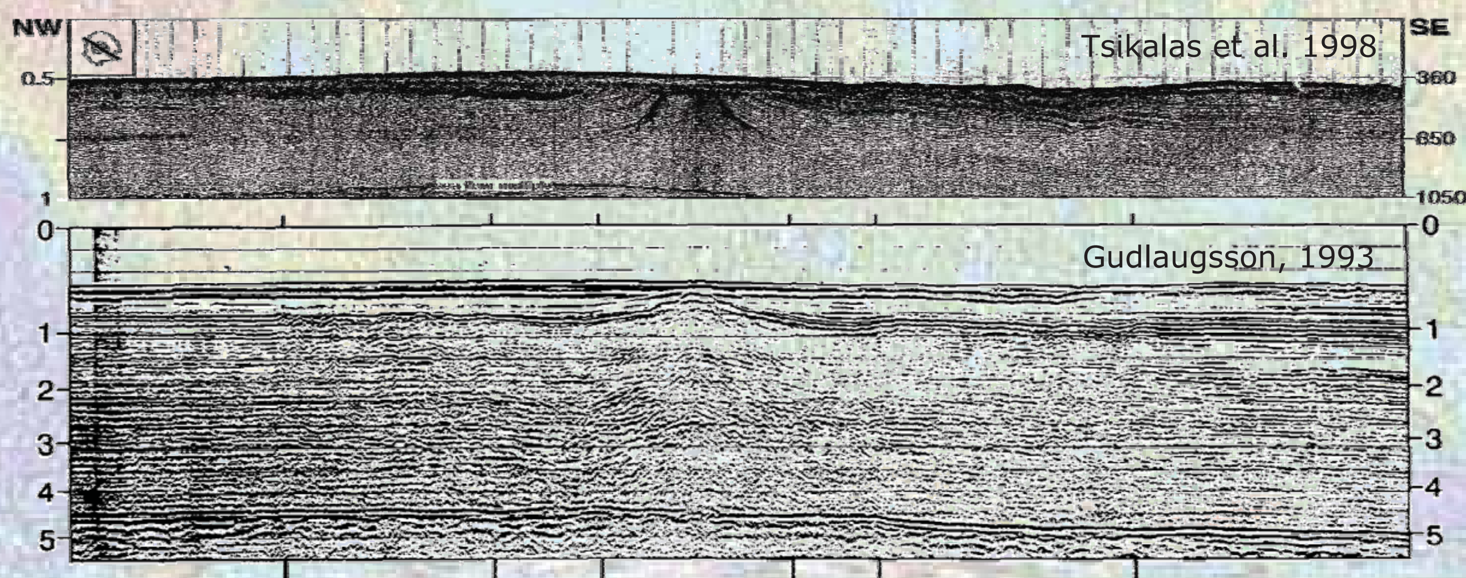


Seismics

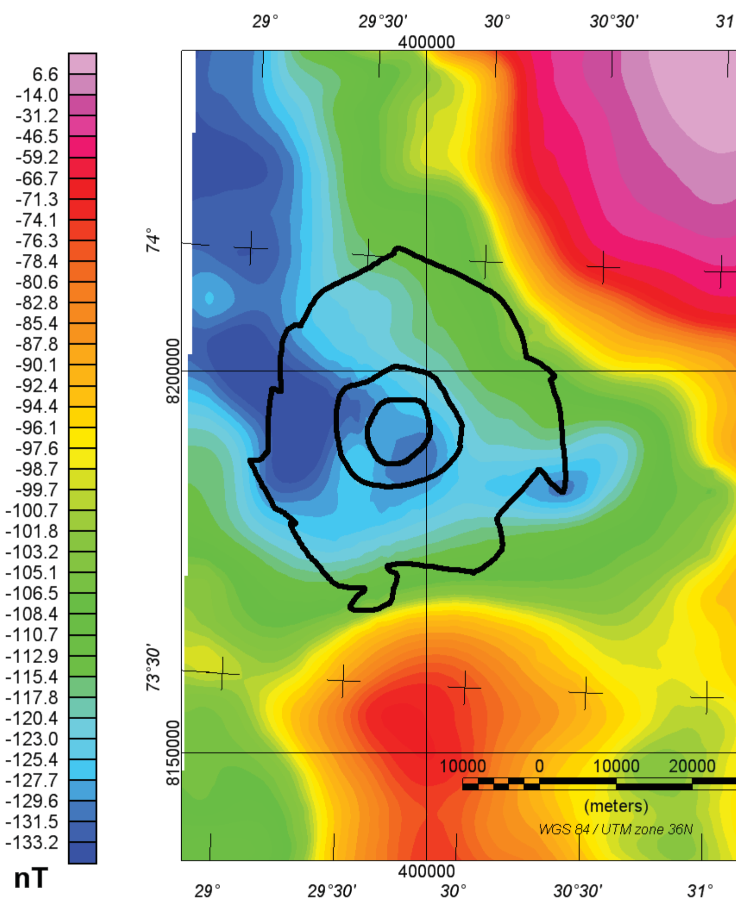
Bjarmeland Platform:

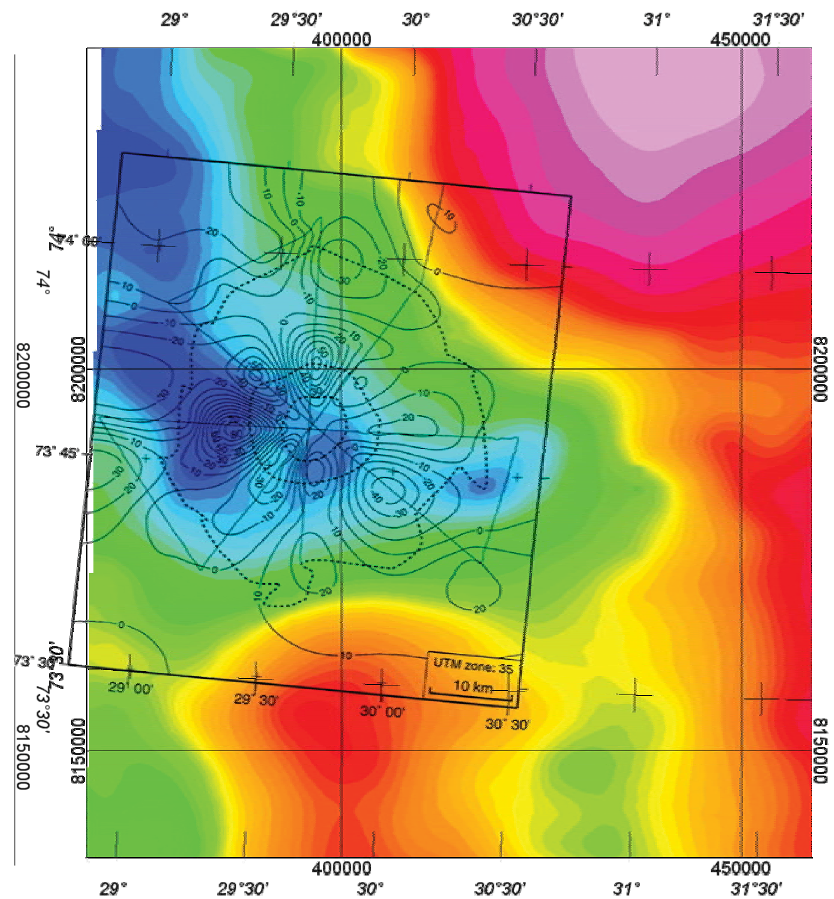
- horizontally layered sedimentary sequences of Devonian to Jurassic
- pronounced horizontal reflector marking the top of the Permian succession (Barents-Sea wide)

- TopPermian reflector remains undisturbed by the impact



Aeromagnetic Survey (BAS06)





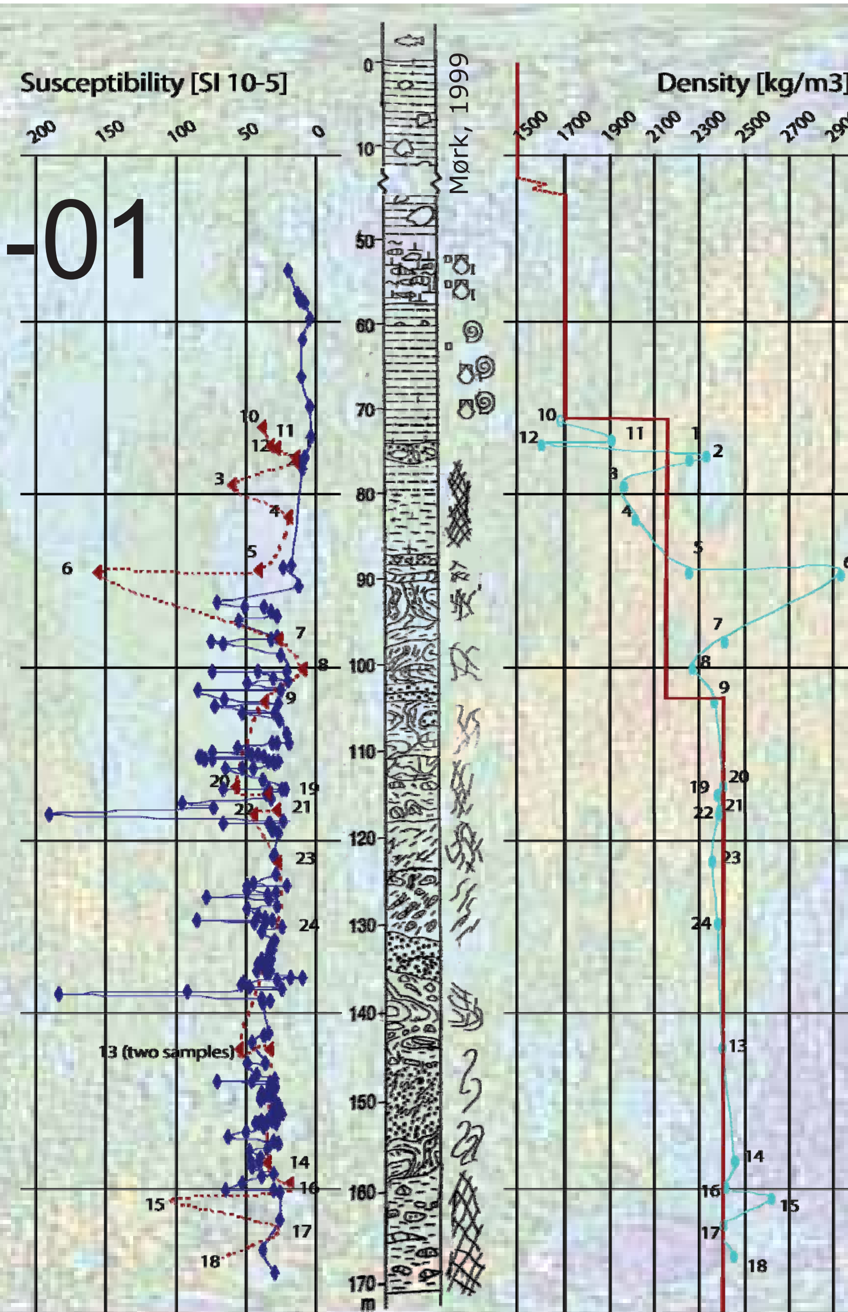
Sponsored by Chevron, EniNorge, Norwegian Petroleum Directorate, RWE-Dea Norge and StatoilHydro.
L. Gernigon and J.O. Mogaard collected and processed the survey data.

Core 7329/03-U-01

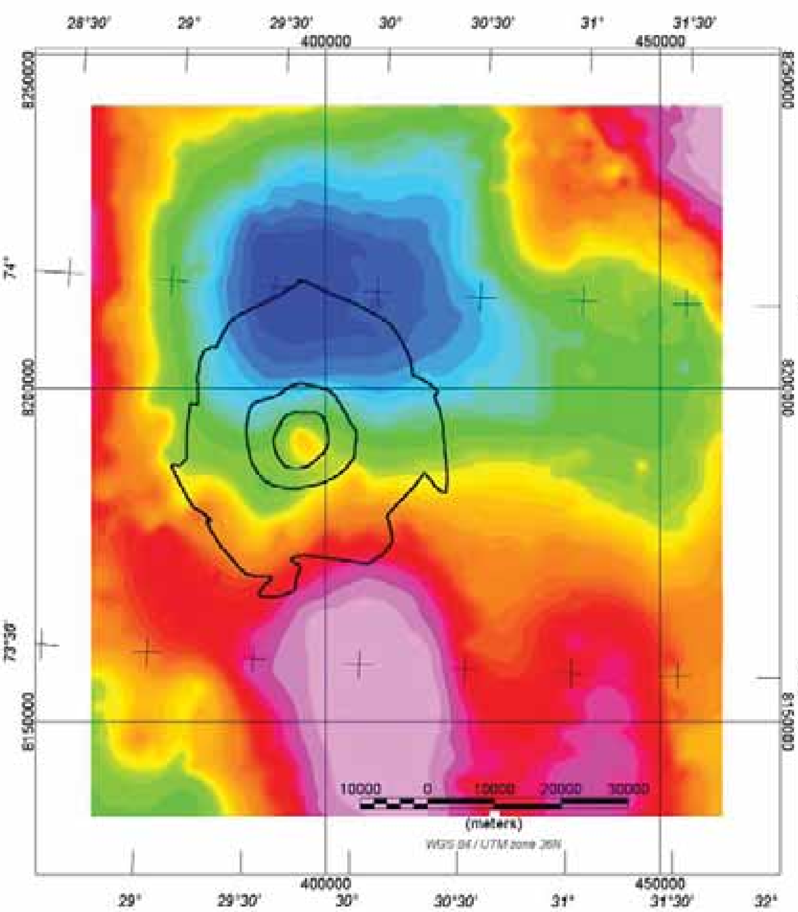
- close to structure centre, depth 171m

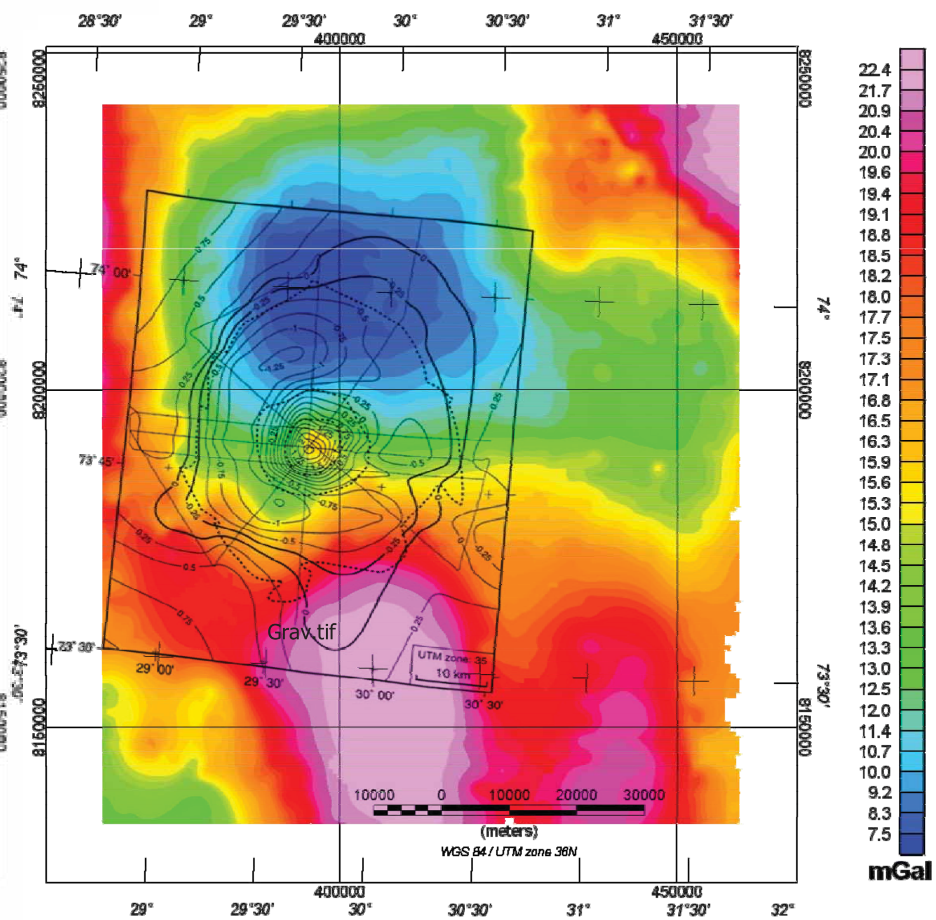
- total susceptibilities: Bartington MS2c sensor in core-scanning set-up
- volume-specific susceptibilities

- range: 0-200 $SI10^{-5}$; typical values for marine sedimentary rocks
- peak values found for siderite-cemented beds or nodules
- other sources are detrital magnetic minerals



Gravity





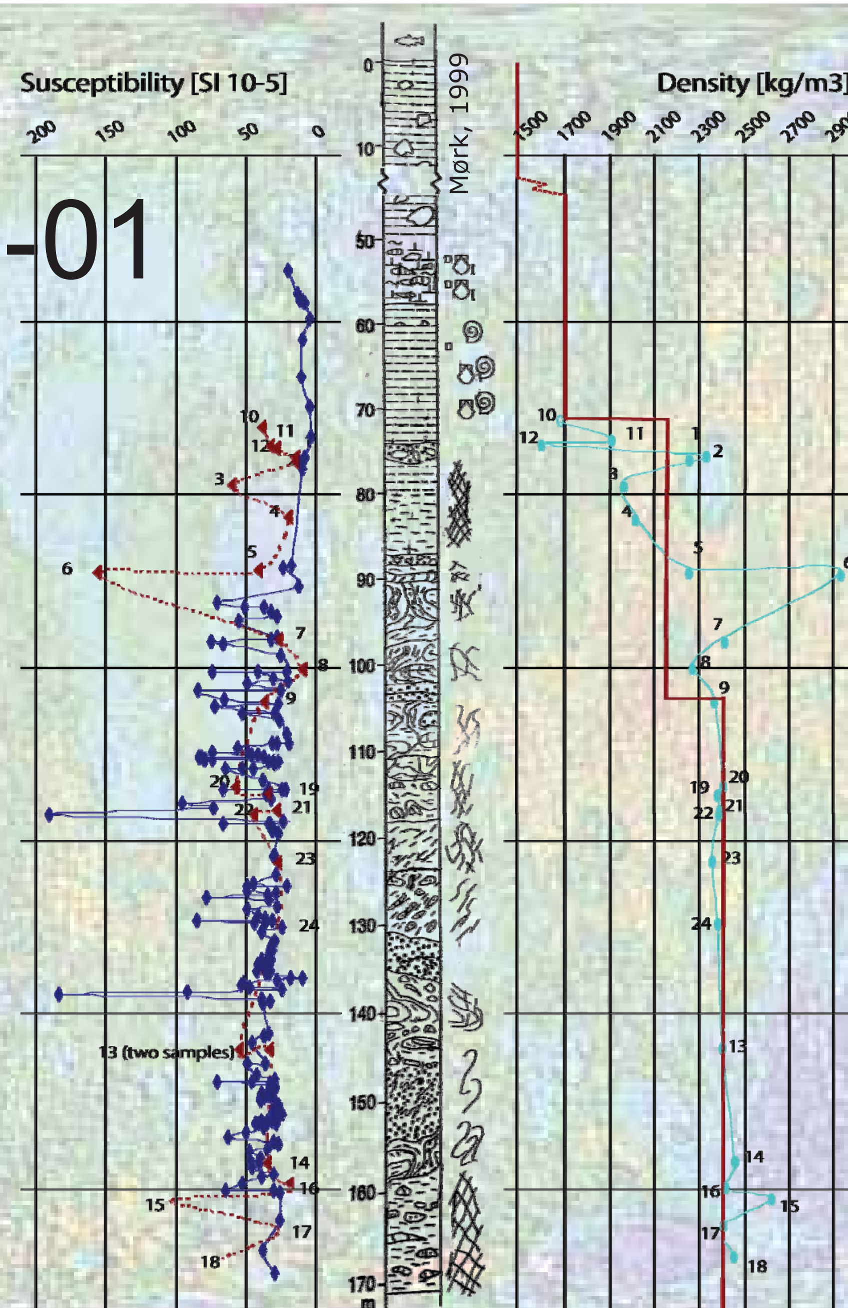
NGU database

Core 7329/03-U-01

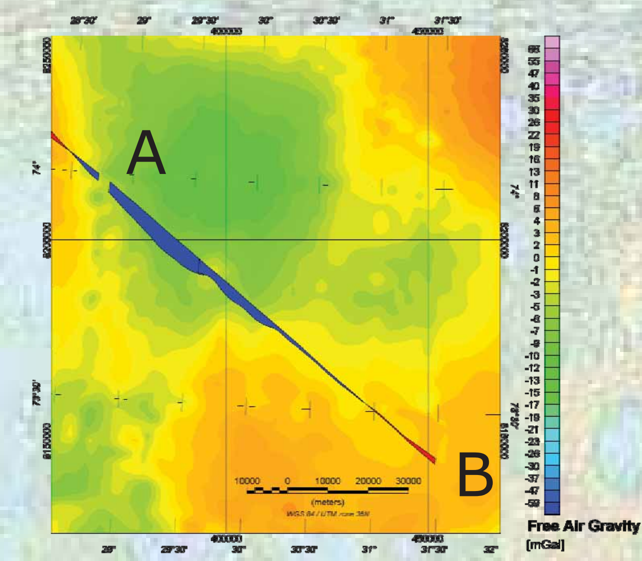
- close to structure centre, depth 171m

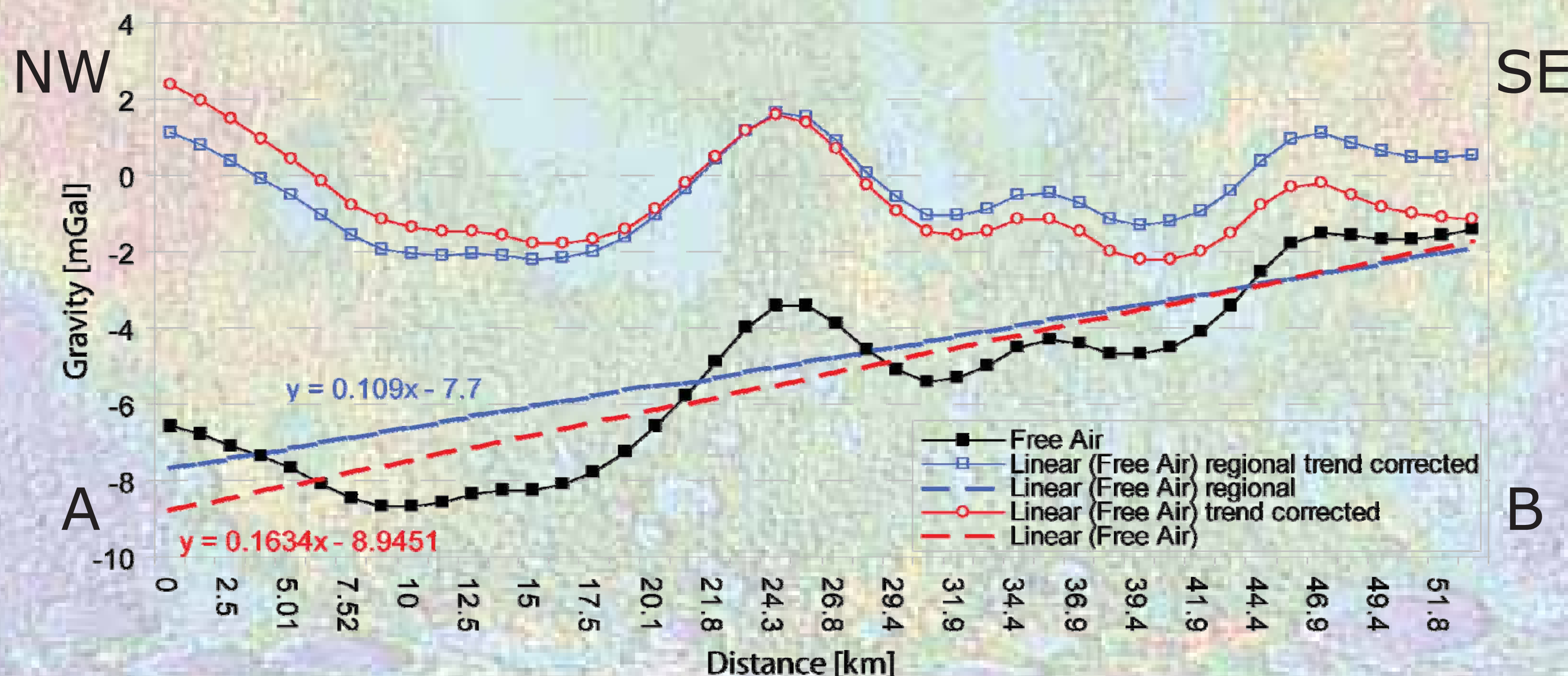
- dry bulk densities (most samples dissolve in water)
- range 1500 –2900 kg/m^3

- were used to constrain the uppermost layers of the gravity model



Regional Trend





Modelling Results

Water:
1030 kg/m^3

Unconsolidated Sed.1:
1500 kg/m^3

Unconsolidated Sed.2:
1700 kg/m^3

Consolidated Layered Sed.:
2150 kg/m^3

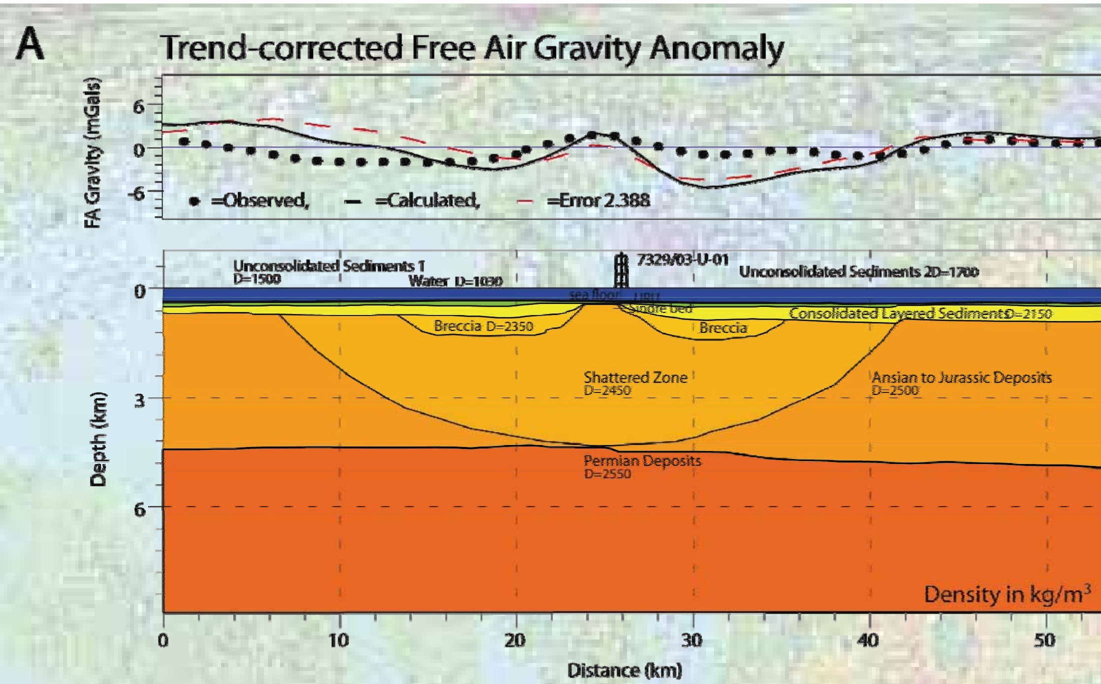
Breccia:
2350 kg/m^3

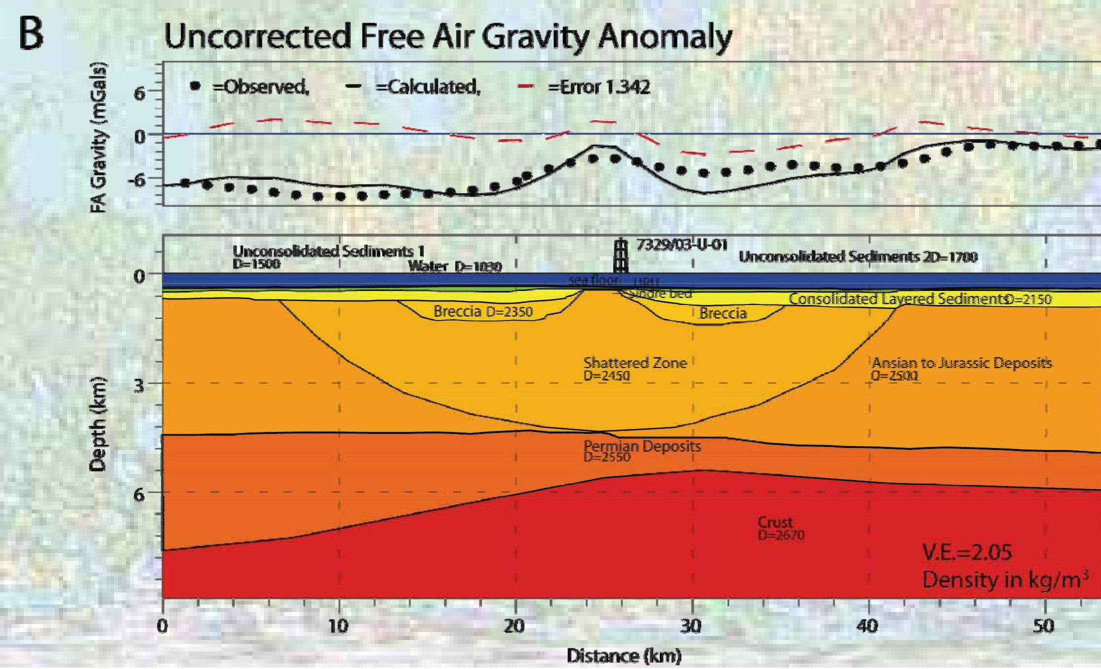
Shattered Zone:
2450 kg/m^3

Ansian to Jurassic Deposits:
2500 kg/m^3

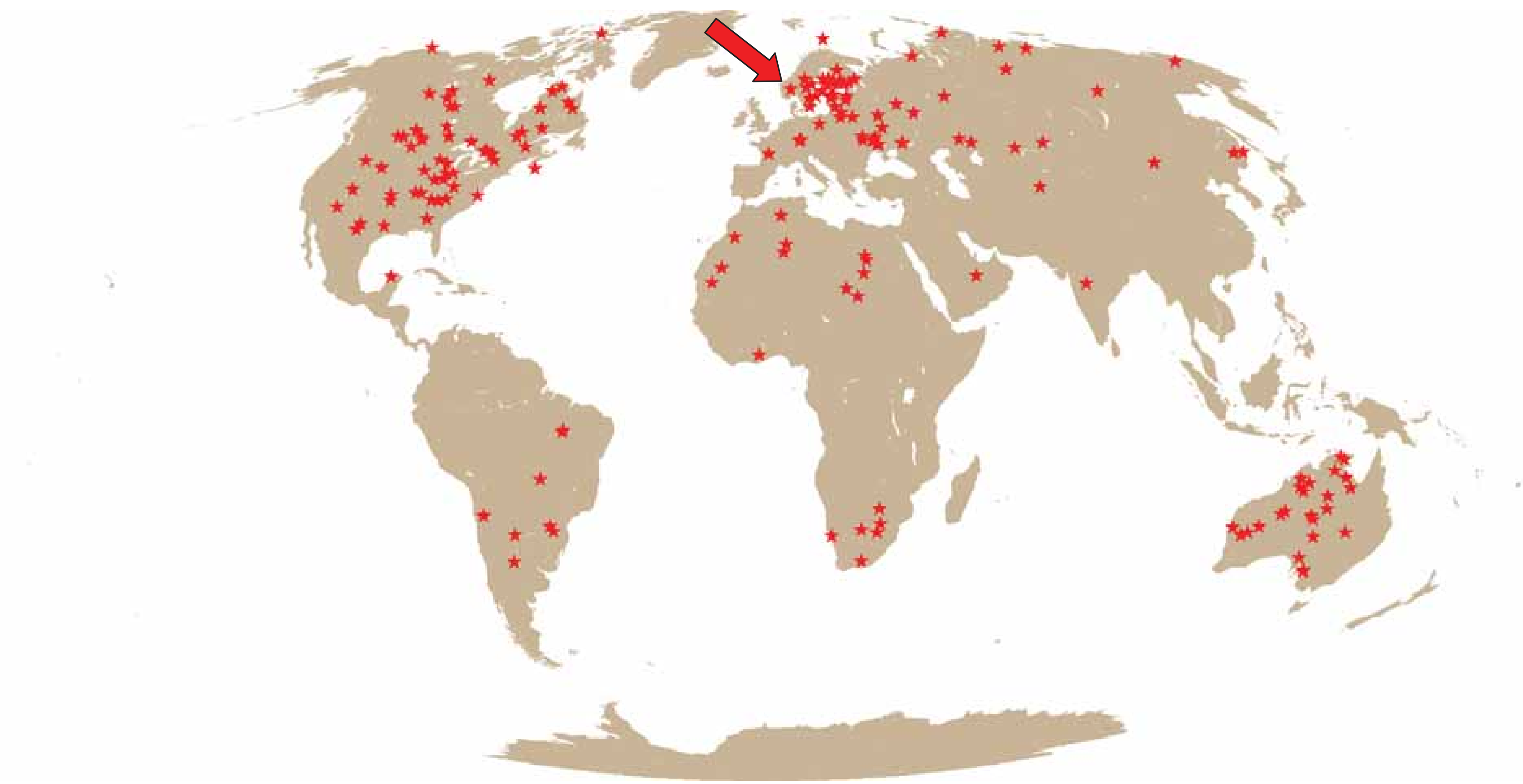
Permian Deposits:
2550 kg/m^3

Crust:
2670 kg/m^3

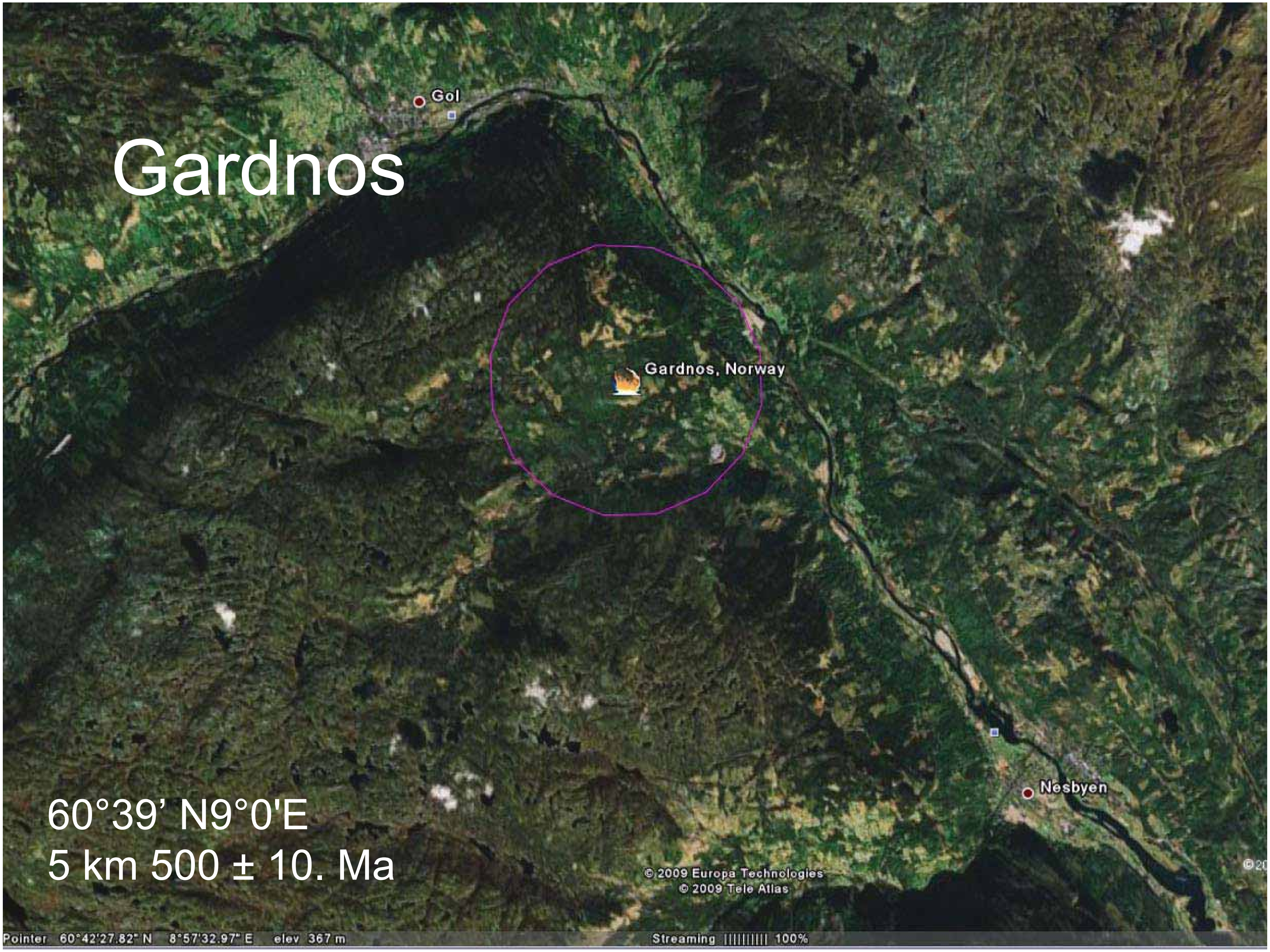




Global Crater Distribution

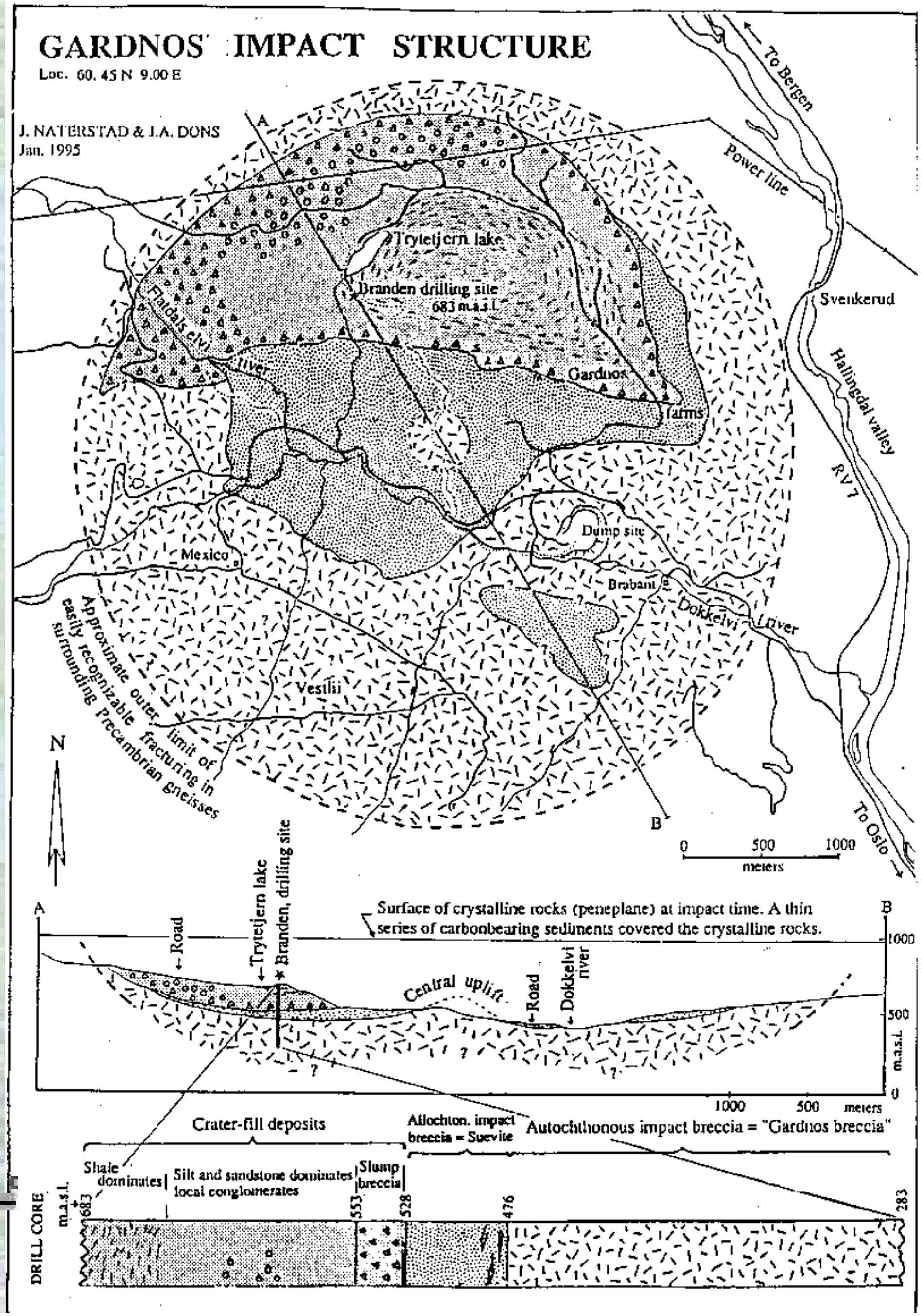


http://www.unb.ca/passc/ImpactDatabase/


Gardnos
Gol
Gardnos, Norway
Nesbyen
60°39’ N9°0'E
5 km 500 ± 10. Ma
© 2009 Europa Technologies
© 2009 Tele Atlas
Pointer 60°42'27.82" N 8°57'32.97" E elev 367 m
Streaming |||||||||| 100%

Gardnos

Gravity and Magnetic Anomaly Maps



Summary

- main attribute: *circularity*
- useful to describe the structural features
- though no proof for impact origin, good for *crater detection*
- *Gravity:* generally negative anomaly
- Magnetics: complex and dependent on the presence of magnetic mineral assemblages
- Seismics: structural information
- Other Methods: general mapping
- *Modelling* is needed for more information subsurface structures
- Calibration utilising properties measured in drill cores