BASICS OF IMPACT CRATERING & GEOLOGICAL, GEOPHYSICAL, GEOCHEMICAL & ENVIRONMENTAL STUDIES OF SOME IMPACT CRATERS OF THE EARTH

IAP 2008 12.091 Special Topics Course
January 8 – 22, 2008

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SESSION 3: January 15, 2008

COURSE OUTLINE

1. **Introduction to terrestrial impact cratering**
2. **Review of some major research studies of terrestrial impact craters**
3. **Tools of analysis**
4. **Chesapeake Bay Impact Crater: Environmental and Geochemical Research Studies**
5. **Summary**

DETAILED COURSE WORK

The course work involves the following:

- **January 8, 10, 15, 17, 22 10 AM to Noon**
- **5 sessions each of 2 hours - 25%**
- **Study/work assignments – 4 - 20%**
- **Project**

  Literature Survey &

  Writing a report - 30%
- **Project Presentation - 25%**
- **Required percentage to pass this course is 95%**
- **Grading: P/F**

Session 3

Tools of Analysis

OBJECTIVE

1. Fundamental events of impact cratering
2. Basic principles of aeromagnetic survey measurement
3. Basic principles of gravity anamoly measurement
4. Phenomenology of impact cratering
5. Determination of impact cratering parameters
6. Concepts of hydrocode modeling
7. Age determination by conventional K – Ar method
8. Neutron Activation Analysis
9. Inductively Coupled Plasma Mass Spectrometry
10. Electron microprobe analysis

1. Fundamental events of impact cratering

Scientists, typically, divide the formation of an impact crater into three main stages:

1. contact and compression,
2. excavation,
3. modification.

Ref: Melosh (1989) & French (1998)

1. Contact and compression:

A high-speed impact

- causes a sudden compression of the projectile
- causes a sudden compression of the target materials at the impact surface,
  - generates a shock wave that propagates through projectile
  - generates a shock wave that propagates through target.

A progressive shock wave

- changes the thermodynamic state of the materials rapidly,
- changes are irreversible; from initial state to the shocked state,
- the thermodynamic changes are very rapid
- the shock is treated mathematically as a discontinuity in material characteristics.

1. Fundamental events of impact cratering ...

- A rarefaction wave
  - reflects back when the shock wave reaches the rear end of the projectile
  - the target surface releases the previously compressed material to low pressures.
- Speed of the rarefaction wave is greater than that of the hemispherically-expanding shock wave.
- The shock wave finally achieves the shape of a thin shell.

2. Excavation

- Particle velocity of the target is the material velocity. This opens the crater during the excavation stage.
- The material velocity has a radial component,

  and a complementary tangential component,
  - tending to deflect the particle trajectories towards the surface,
  - pushing material into the target,
  - expelling material from the expanding crater.

3. Modification Stage

- The final stage of the cratering process is the modification stage which causes collapse of the crater.
- This crater collapse is due to gravity-driven modification of the unstable cavity formed during excavation.
- Ultimately a shallower, more stable in a gravity field, crater forms.
- For simple craters the collapse process is well understood.
- For larger, morphologically more complex impact structures, collapse is not well understood.

2. Basic Principles Of Aeromagnetic Survey

Aeromagnetic survey

Measures intensity of the Earth's magnetic field using magnetometers mounted in an airplane or helicopter.

The differences between actual measurements and theoretical values represent anomalies in the magnetic field.

The anamolies in turn represent changes in rock type or thickness of rocks.

The contour maps generated from the survey provide information to consider whether there is crater or other geologic formation in that region.

2. Basic Principles Of Aeromagnetic Survey ...

- Aeromagnetic surveys are conducted on a wide variety of terrains; with varying sampling rates, and line spacings.

- Contour maps represent the results.

- The survey grid defines the continuous magnetic field sufficiently well to justify interpolation.

Ref: A. B. Reid , Aeromagnetic Survey Design,
Geophysics Vol.45 No.5 (May 1980) p 973-976.

2. Basic Principles Of Aeromagnetic Survey ...

Aeromagnetic measurement parameters:

- The spatial wave length λ_N and spacing Δx of line of samples are related by the Nyquist equation

  $$\lambda_N = 2 \Delta x \quad (1)$$

Hence, it is very important to determine a priori the most appropriate value for Δx in terms of height of the sensor above source bodies.

2. Basic Principles Of Aeromagnetic Survey …

Aeromagnetic measurement parameters …

- $<C^2(r)>$ approaches unity for sources of considerable depth extent.
- $<S^2(r)>$ approaches unity for sources of small upper surface area.
- So the equation (1) reduces to

$$<E(r)> = 4\Pi^2 k_m^2 \exp(-2h_m r)$$

Ref: A. B. Reid , Aeromagnetic Survey Design, Geophysics Vol.45, No.5 (May 1980) p 973-976.

2. Basic Principles Of Aeromagnetic Survey ...

Aeromagnetic measurement parameters …

- **For a given survey spacing** Δx, **there will be a Nyquist wavenumber** r_N **and is given by**
  $r_N = 2\Pi / \lambda_N = \Pi / \Delta x$

  The fraction of the power
  $F_T = \exp(-2\Pi h_m / \Delta x)$

  h_m **= mean elevation difference between the top surfaces of the magnetic areas and the sensor**

- **Here** Δx **should be taken to be the line spacing or in-line sample spacing, which ever is larger.**

2. Basic Principles Of Aeromagnetic Survey …

The following figures are courtesy of USGS:

Ref: V. J. S. Grauch

High-Resolution Aeromagnetic Survey to Image Shallow Faults, Dixie Valley Geothermal Field, Nevada

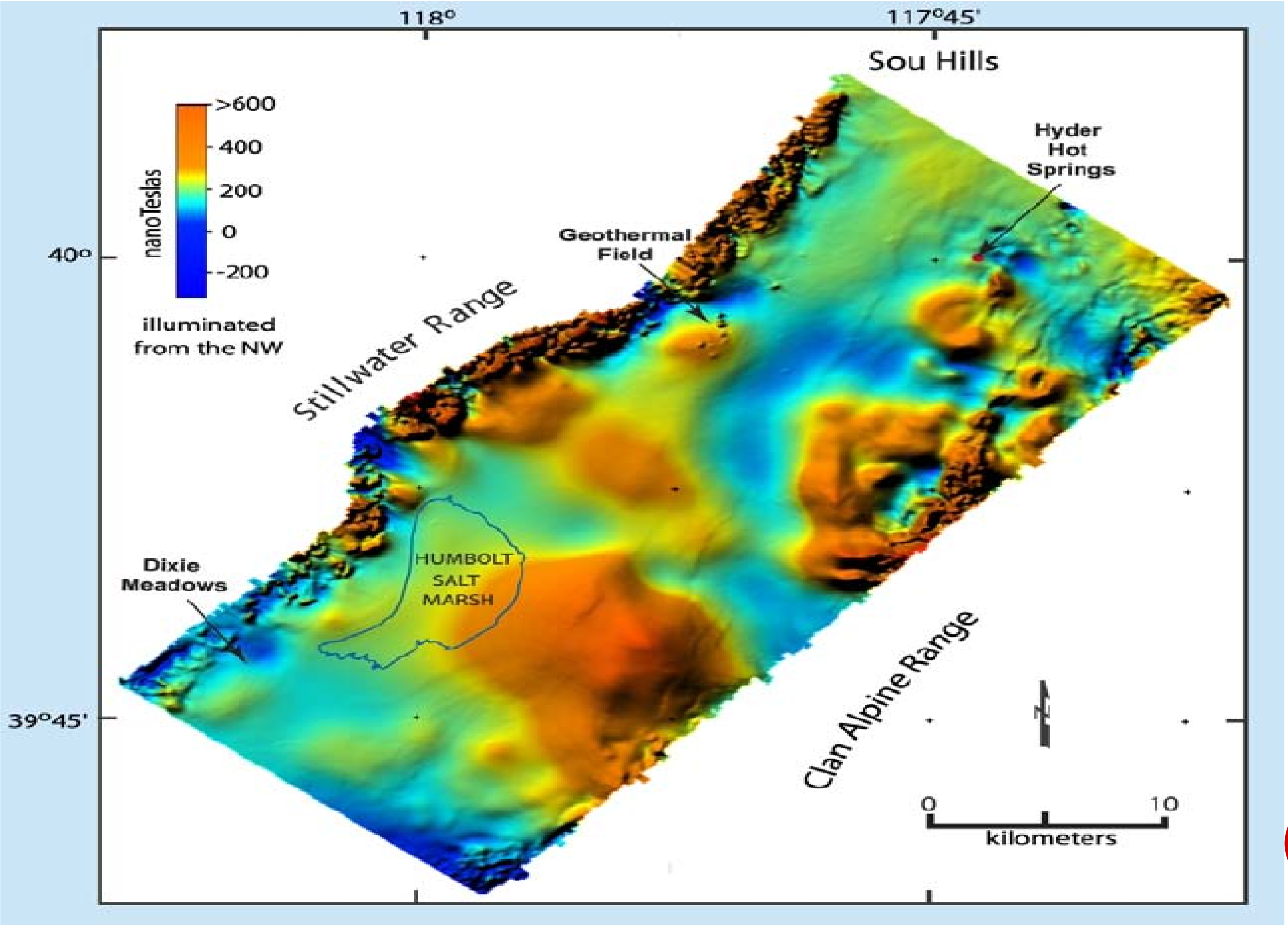
USGS Open File Report ofr-02-0384_508.pdf

Figure 3 p. 6

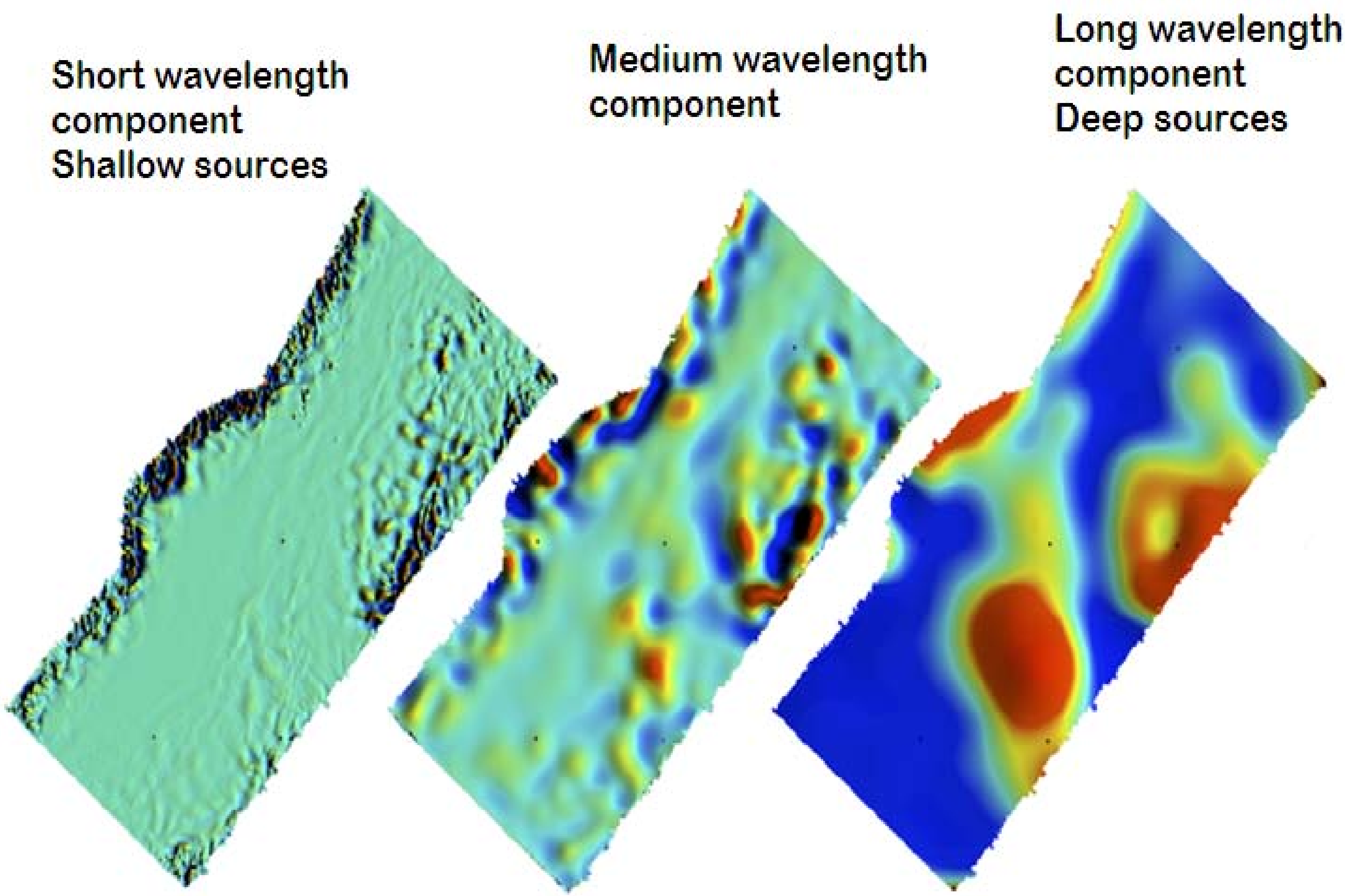
Figure 5 p. 8

Figure 6 p. 9

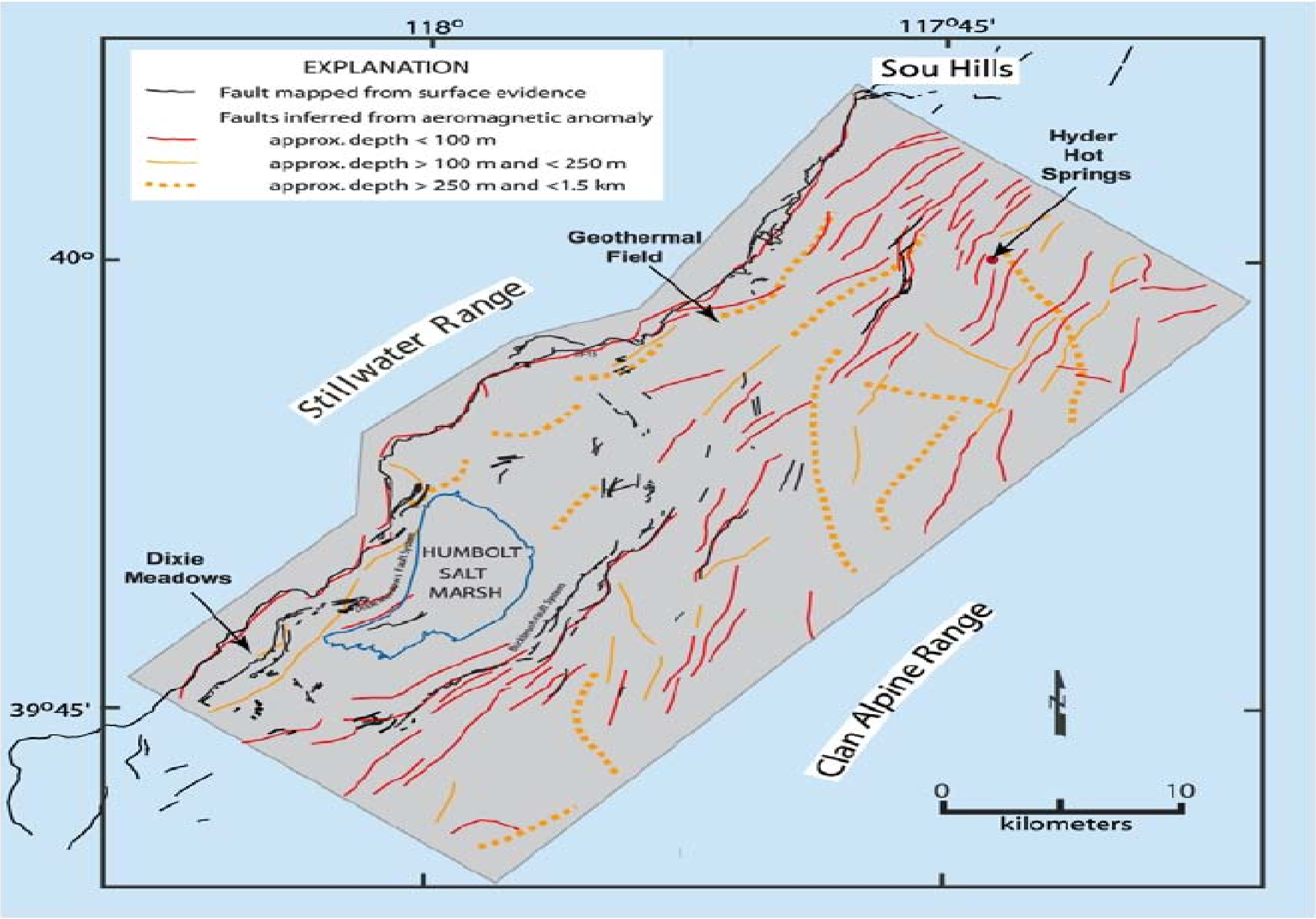
Reduced-to-pole (RTP) aeromagnetic data shown in color shaded-relief, illuminated from the northwest. Figure courtesy of USGS



Separation of the Reduced to Pole aeromagnetic data into different anomaly-width (depth) components using matched filtering. Figure courtesy of USGS.



Interpreted faults, color-coded according to estimated depth, compared to faults mapped at the surface from Smith et al. (2001). Figure courtesy of USGS.



3. Basic Principles Of Gravity Anamoly Measurements

- Gravity is one of the universal forces of nature. It is an attractive force between all things. The gravitational force between two objects depends on their masses, and the distance between them.
- Gravitational force can be observed when at least one of the objects is very large (like the Earth).
- Gravity surveying consists of looking at the subsurface structure based on the differences in densities of the subsurface rocks.
- Gravity anamoly variations can give ideas about depth, size and shape of the body of interest.
- Earth's gravity of acceleration is

  980 cm /s^2 or 9.80 m /s^2

3. Basic Principles Of Gravity Anamoly Measurements …

Velocity = distance/time   cm/s or m/s

Acceleration = velocity/time cm/s^2 or m/s^2

Gravitational Unit   (GU or gu)

1 gu = 1 $\mu m/s^2$

Also expressed as 10 milliGals = 1gu

Force between two bodies is inversely proportional to the square of the distance between them.

Newton's law of universal gravitation force

$F = G\, m_1 m_2 / r^2$

Where

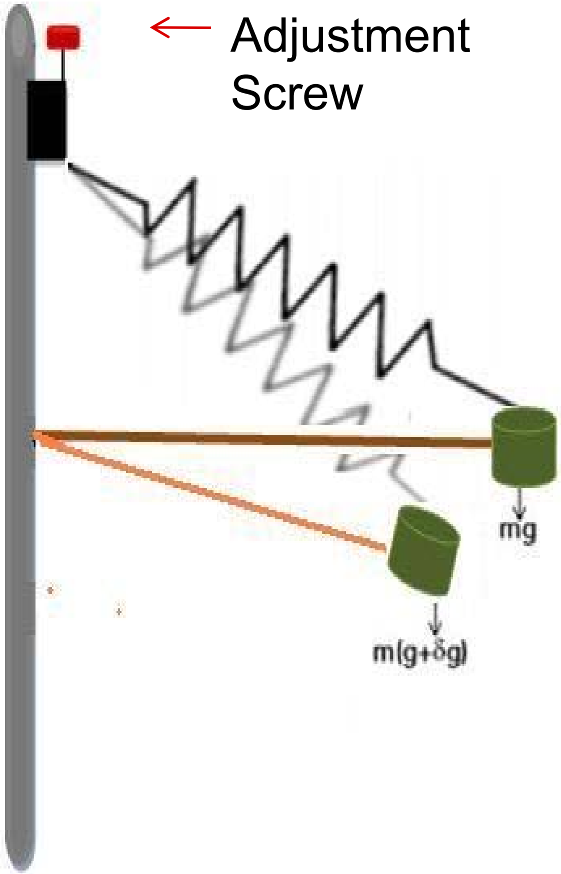
G = Universal Gravitational Constant

($6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$),

m_1 and m_2 are two bodies separated by distance r.

3. Basic Principles Of Gravity Anamoly Measurements ...

- Gravitational field measured by using a typical device like LaCoste & Romberg gravimeter. The device consistof very sensitive spring and mass of weight. The weight is attached to a beam and a spring .
- As gravity increases, the weight is forced downwards, stretching the spring.
- By adjusting a screw, the beam is brought back to horizontal position.
- Gravitational force is proportional to the amount of movement required.



3. Basic Principles Of Gravity Anamoly Measurements …

- The gravitational field is mapped using the gravitational potential, U.

  Potential = Force x distance
- U = GM/r

Ref:

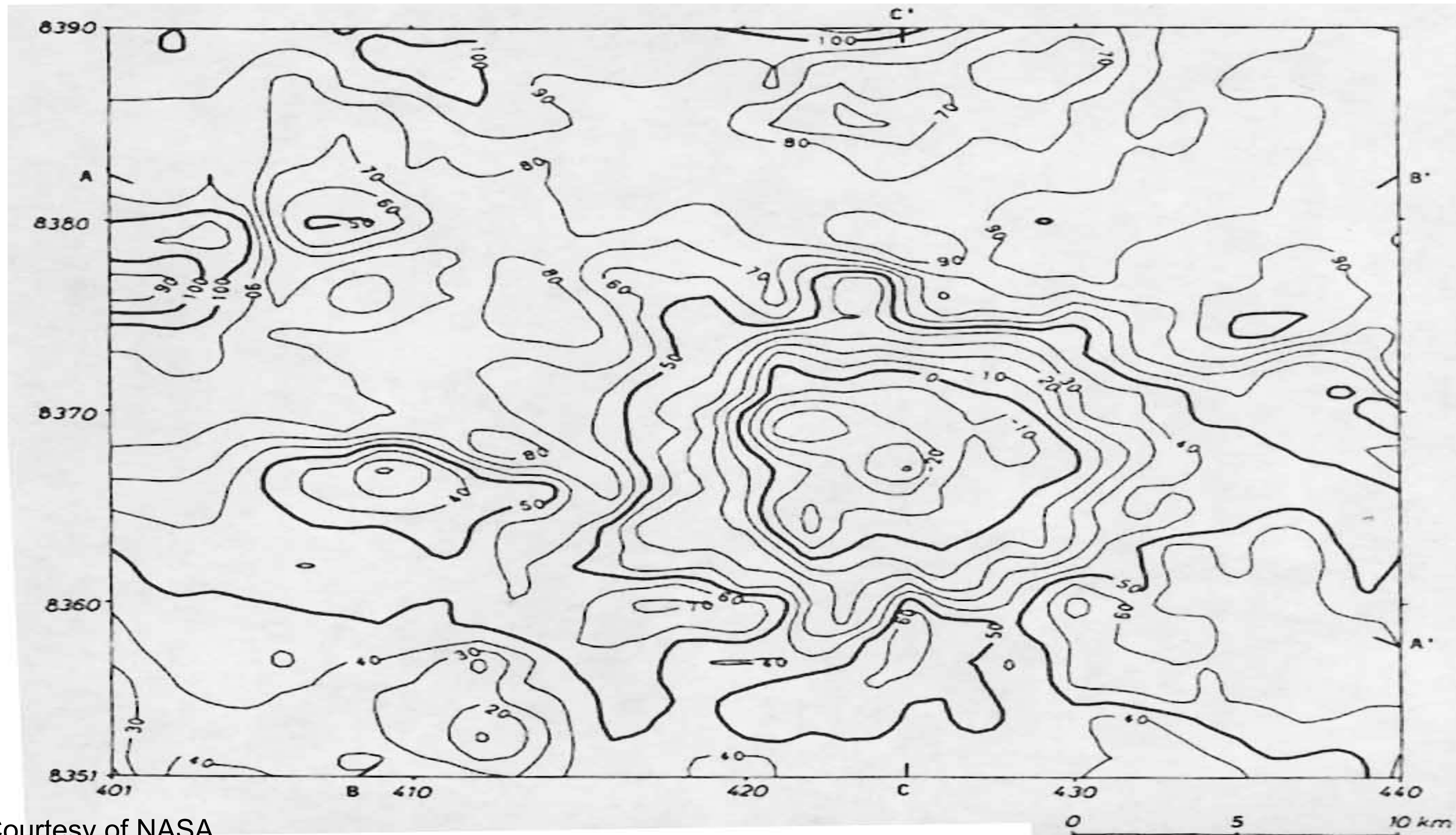
- P. Keary & M. Brooks, 1991.

  An Introduction to Geophysical Exploration.
- W. Lowrie, 1997.

  Fundamentals of Geophysics.

3. Basic Principles Of Gravity Anamoly Measurements …

Contour map of Haughton impact structure negative anamoly



Courtesy of NASA

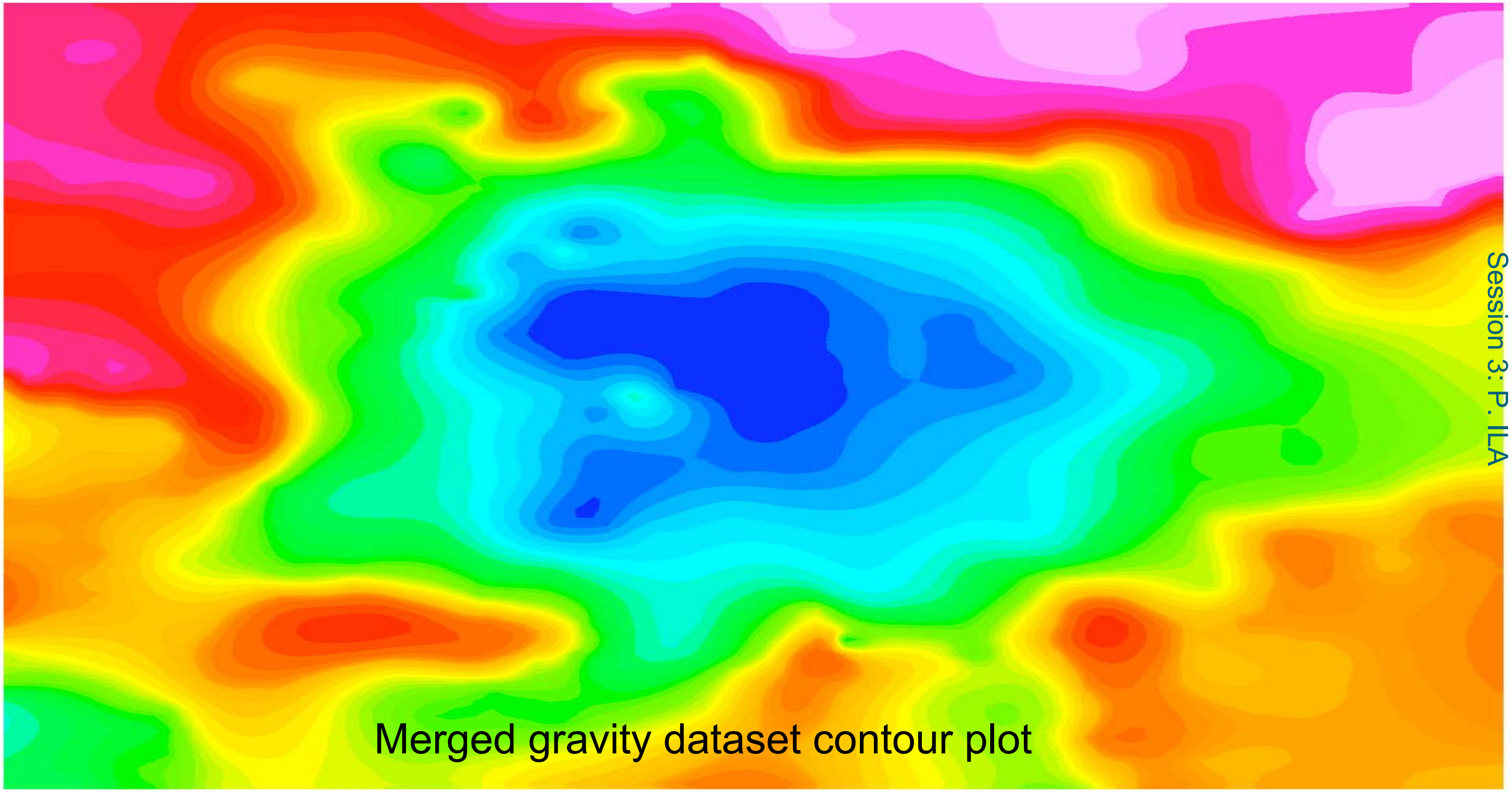
Ref: http://ti.arc.nasa.gov/publications/pdf/0953.pdf

B. J. Glass, S. Domville and P. Lee

Further Geophysical Studies of the Haughton Impact Structure

Figure 2. Gravity survey showing central Bouger negative anomaly.

3. Basic Principles Of Gravity Anamoly Measurements ...



Courtesy of NASA

Ref: http://ti.arc.nasa.gov/publications/pdf/0953.pdf

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Further Geophysical Studies of the Haughton Impact Structure

Figure 3. Merged gravity dataset contour plot.

4. Phenomenology of Impact Cratering

Quantitative models

- Physical quantification of the mechanics involved in meteorite impacts:
  - Impactor traveling with hypervelocity
  - Final impact dynamics
    - diffusion,
    - turbulence of flight,
    - geometry,
    - rotation of flight,
    - aerodynamic pressure,
    - drag and energy transfer,

4. Phenomenology of Impact Cratering

Quantitative models …

Final Impact parameters …

- **ablation,**
- **radiation,**
- **target density,**
- **atomic collision,**
- **potential energy of atomic interaction,**
- **shock wave propagation,**
- **cratering,**
- **melting,**
- **oblique impacting**

5. Determination of Cratering Parameters

In the words of Melosh (1980):

- "To gain a basic understanding of the sheer magnitude and striking spectacle that is a meteorite impact, it may be more effective (if not more understandable) to focus on simple energy relationships"
- "This approach has been quite successful for small meteorite impacts, however for large scale impacts, our ability to understand the processes involved decreases as the size of the meteorite increases."

Impact energy of a meteorite

The impact energy of a meteorite can be estimated by calculating its kinetic energy from its size (of certain radius) and speed (velocity of impact).

Total Kinetic Energy $= (\frac{1}{2})MV^2$.

The units can be in

g cm^2/sec^2 or kg m^2/sec^2 .

M = Mass of the meteorite kg .

V = velocity of the meteorite km/sec .

5. Determination of Cratering Parameters ...

- Units of energy

  Joule

  $$J = kg \times m^2 / s^2$$

  Erg

  $$Erg = g\ cm^2/s^2$$

- Giga Joules (GJ).

  $1\ GJ = 10^9\ J$

- 1 million tons of dynamite equivalent is

  $1\ Mt = 4 \times 10^{15}\ J.$

5. Determination of Cratering Parameters …

- Consider some realistic limits for the parameters.

- Velocity of a meteorite must be at least 11 km/s.

  Reason being,

  this is the estimated minimum velocity for a projectile shot from earth to overcome gravity and reach space.

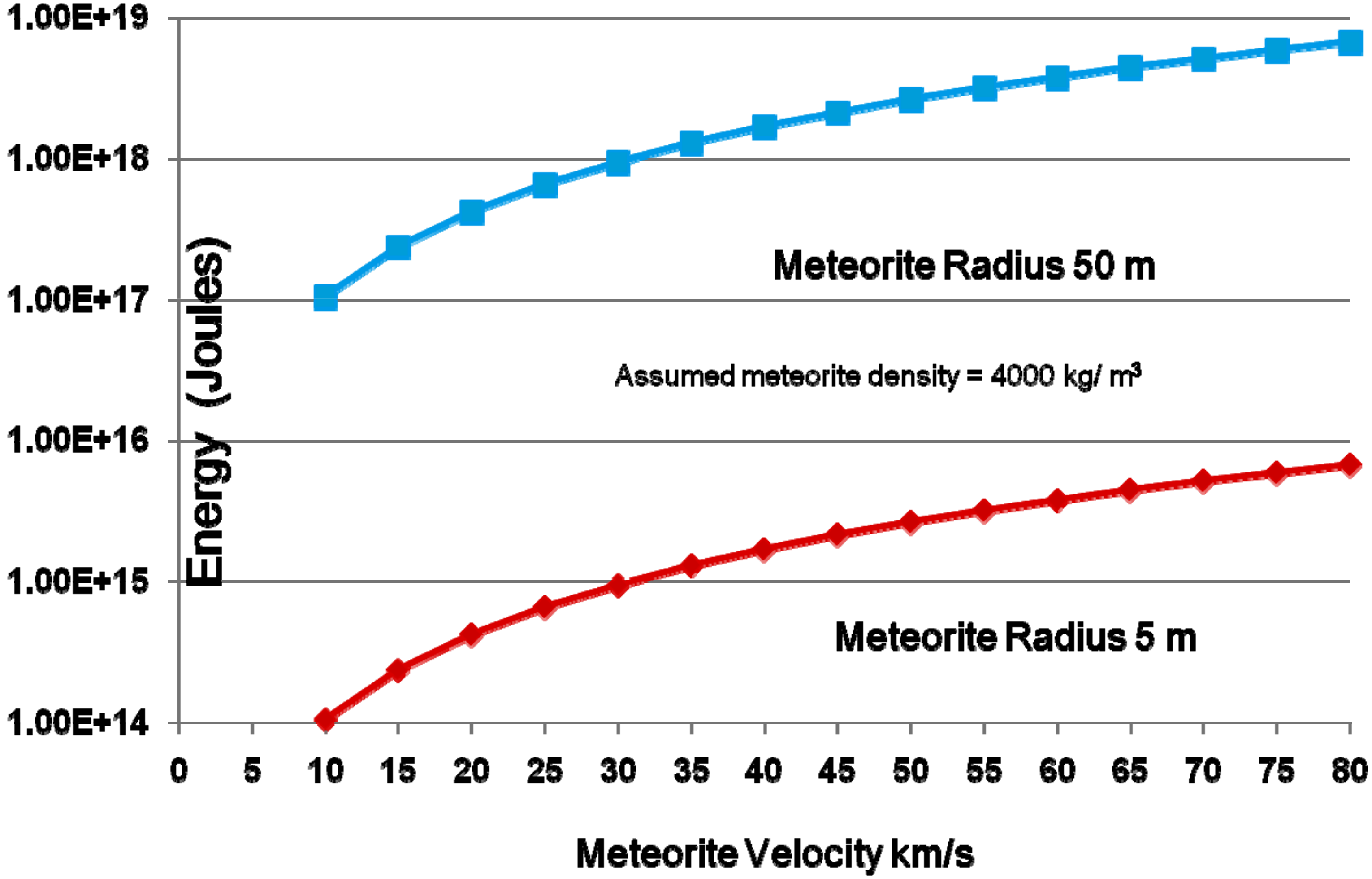
- Conversely, any thing falling from space to earth must achieve the same velocity.

- Upper value for the velocity 72 km/s

  Ref: Middleton and Wilcock (1994).

5. Determination of Cratering Parameters …

METEORITE SPEED VS. ENERGY



5. Determination of Cratering Parameters

Mass of the meteorite:

Mass = Volume x Density

$M_m = V_m \times \rho_m$

Volume of a spherical meteorite of radius R_m

$= (4/3)\Pi R_m^3$

Example:

- Iron meteorite

  density = 8000 kg/m^3

- Stony meteorite is

  density = 3500 kg/m^3.

From these observed values, meteorite density range could be visualized.

5. Determination of Cratering Parameters …

- The diameter of the meteorite, hence the radius R_m of the meteorite is unknown, because we are interested in estimating the size of the meteorite.
- The probable density range

  3500 kg/m^3 to 8000 kg/m^3
- So a simplistic numerical model is to vary the parameters of diameter, density, velocity in Kinetic Energy formula

Kinetic Energy

$= (\frac{1}{2})MV^2 = (1/2)[(4/3)\,\Pi\, R_m^{\,3}\ \rho_m\,]\ V_m^{\,2}$

5. Determination of Cratering Parameters …

- Impact angle is neglected

An impact at 75 degrees is approximately the same as using a diameter 3/4 as big as the original diameter
or
using a density that is 3/4 the original density of the meteorite.

5. Determination of Cratering Parameters ...

Estimation of energy of the meteorite to a first approximation:

Assumptions

1. Formation of a simple crater

   The shape of crater is a simple bowl

2. The impact energy is 100% from impactor to the target

   Kinetic Energy of the meteorite

   = Potential Energy of the Crater

5. Determination of Cratering Parameters ...

- Potential Energy of the crater

  =

  volume of rock that will be displaced (V_r)

  x rocks density (ρ_r),

  x gravity of the planet the meteorite is impacting (in this case, earth) (G_E)

  x height of crater formation (h).

$PE = V_r * \rho_r * G_E * h$

5. Determination of Cratering Parameters …

- **Consider the hemispherical crater of radius the R_{Crater}**

Assumption:

- **Height of the ejected impacted rock (h) be equal to R_{crater} ,**

$h = R_{crater}$.

Then,

$$Energy_{meteorite} = (1/2)[(4/3)\Pi * \rho_r * G_E * R_{crater}^{3}] R_{crater}$$

$$= (2/3)\Pi * \rho_r * G_E * [R_{crater}]^4$$

5. Determination of Cratering Parameters ...

But not all of the meteorite's energy transforms into potential energy for the formation of the crater.

Estimations show that

80% - 95% meteorite's energy is consumed in

- shock wave production
- heat production

Melosh (1985), Holsapple and Schmidt (1987).

5. Determination of Cratering Parameters ...

$$E_{meteorite} = E_{cratering} + E_{heat} + E_{shock\ wave}$$

is a simplistic equation.

Target rock characteristics effect calculations of

shock propagation speed and

particle velocity

amount of heat produced

resulting amount of melt

Calculations are complicated and at the most are approximations only.

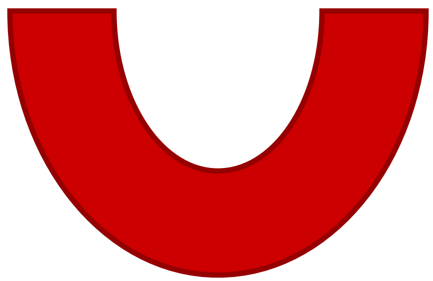
Melt Volume Calculations

Melt Volume =

Total volume of the hemispherical Crater bowl

- volume of crater bowl with a diameter of

{ d-(2*0.05d)}.



Assumption:

Melt thickness = 0.05 *diameter of the crater

4% to 6% of the diameter of the crater is equal to the thickness of the melt layer produced.

Ref: O'Keefe and Ahrens (1994)

5. Determination of Cratering Parameters …

Through a series of 3D hydrocode simulations, Pierazzo and Melosh (2000b) conclude:

- For constant impact conditions but varying impact angle, impact melt volume decreases by
- at most 20% for impacts from 90º (vertical) down to 45º.
- about 50% for impacts at 30º,
- more than 90% for a 15º impact.
- An energy scaling law does not seem to hold for oblique impacts, even if the impact velocity is substituted by its vertical component.

5. Determination of Cratering Parameters ...

"

- During this early impact phase, the impacting body is stopped after about 2 projectile radii and the kinetic energy [$(1/2)mv^2$] is transformed into heat and shock waves that penetrate into the projectile and target.

- The most important phenomenon, which is characteristic of impact, is the generation of a supersonic shock wave that is propagated into the target rock.

"

Shock pressure calculation

Holsapple and Schmidt (1987):

Initial pressure of the shock wave

- $P_{initial} = d_{target} * \ v^2_{meteorite}$
- $v_{meteorite}$ velocity of the meteorite
- P is the pressure of the shock wave at a distance, (**d**) from the crater

5. Determination of Cratering Parameters …

Shock Pressure Calculations …

At impact, approximately

- initial particle velocity

  = [1/2]meteorite's velocity
- initial pressure of shock

  = $d_{target*} v^2_{meteorite}$, where d_{target} = distance from target
- decay of shock wave pressure

  = $1/R_{Crater}^6$ to $1/R_{Crater}^2$, where R_{Crater} is the radius of the impact crater

  Holsapple and Schmidt (1987)
- initial impact pressures for an 11.2 km/s to 30 km/s impact are around 1 to 10 Mega bars.

  Melosh (1980)

5. Determination of Cratering Parameters …

Shock pressure wave calculation …

- $P_{initial} = K_* 1/r^3_{initial}$, where K is a proportionality constant and $r_{initial}$ is the radial distance from point of contact.
- For maximum P, r is approximately equal to the radius of the meteorite $R_{meteorite}$.
- K value can be calculated for various $R_{meteorite}$ and $P_{initial}$ values which in turn are dependent upon initial velocity and target density.
- Using these K value and P value into the above equation, the distance from the impact site where the shock wave would reach this pressure can be calculated.
- Or for various r values of the above equation, shock pressure, P at that distance can be calculated

Oblique Impact

The probability of a meteorite striking a target surface exactly vertically is very small. The most probable angle of impact is 45^o .

The main difference between vertical and oblique impacts is the fate of the impacting meteorite.

The meteorite's material gets compressed by a shock that originates at the contact surface of impact and propagates into the meteorite. The vertical component of the meteorite's velocity gets reduced by the shock, but the horizontal component is still large.

The meteorite penetrates less deeply into the target in an oblique impact than a vertical impact.

5. Determination of Cratering Parameters ...

References for further details on effects of oblique impact :

- Pierazzo E, Melosh H. J., (2000a),
  Hydrocode modeling of oblique impacts: The fate of the projectile,
  Meteoritics and Planetary Science 35: 117-130.

- Pierazzo, E., Melosh, H. J., (2000b),
  Melt production in oblique impacts.
  Icarus 2000, v. 145, 252-261.

- Pierazzo, E., Melosh, H. J., (2000c),
  Understanding oblique impacts from experiments, observations, and modeling.
  Annual Review of Earth and Planetary Science
  2000, v. 28, 141-167.

- Pierazzo,E., Collins, G., (2004),
  A brief introduction to hydrocode modeling of impact cratering, In: Dypvik,D., Burchell,M., Claeys,P., editor, Cratering in marine environments and on ice, New York, Springer, 2004, Pages: 323 – 340.

5. Determination of Cratering Parameters ...

Effects of Oblique impact

- Peak shock pressure contours in the plane of impact for various oblique impacts (angles are measured from the surface) of a projectile 10 km in diameter impacting at 20 km/s can be understood from the figures provided by Pierazzo and Collins (2004) and Pierazzo and Melosh (2000b).

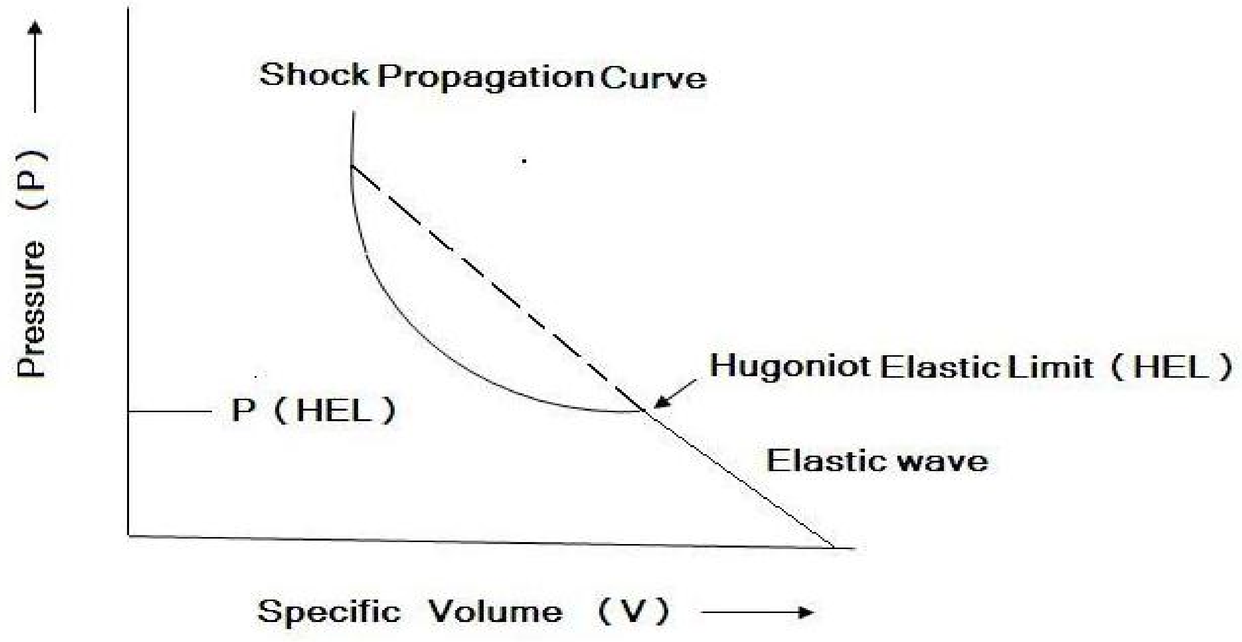
- Pierazzo et al (2000 b) conclude that

  the shape of the region of melting/vaporization is not symmetrically distributed around the impact point for oblique impacts, but the shape progresses downrange from the impact point.

Hugoniot Elastic Limit

- The shock wave causes compression of the target rocks at pressures far above a material property called the Hugoniot elastic limit (HEL).
- The Hugoniot elastic limit is the maximum stress in an elastic wave that a material can be subjected to without permanent deformation.
- Above this limit plastic, or irreversible, distortions occur in the solid medium through which the compressive wave travels .
- In addition to structural changes, phase changes may occur as well.

5. Determination of Cratering Parameters …



Pictorial Representation of Hugoniot Elastic Limit

Ref: Impact Cratering: An overview of mineralogical and geochemical aspects;
after: Koeberl, C., 1997, Impact cratering: The mineralogical and geochemical evidence. In: Proceedings, "The Ames Structure and Similar Features", ed. K. Johnson and J. Campbell, Oklahoma Geological Survey Circular 100, 30-54.

5. Determination of Cratering Parameters ...

- The only known process that produces shock pressures exceeding the HELs of most crustal rocks and minerals in nature is impact cratering.
- Volcanic processes are not known to exceed 0.5 to 1 GPa.
- Values of the HEL for some minerals and whole rocks.
  - Quartz 4.5 to 14.5 GPa
  - Feldspar 3 GPa,
  - Olivine 9 GPa.
  - Dolomite 0.3 GPa,
  - Granite 3 GPa,
  - Granodiorite 4.5 GPa.

  Ref:Table 3.1, p . 35,Impact Cratering – A geologic Process . H. Melosh (1989).

5. Determination of Cratering Parameters …

Hugoniot Equations …

- The parameters of the one-dimensional flow behind a planar shock wave are obtained by application of the conservation laws of mass, momentum, and energy across this wave.
- By choosing a coordinate system fixed in the undisturbed medium, one may derive the familiar Rankine-Hugoniot equations

Hugoniot Equations

For a thermodynamical treatment of shock fronts travelling through matter, the so-called Hugoniot equations are used (Ref: Melosh, 1989).

These equations link uncompressed (initial)

the pressure P,

internal energy E,

density ρ in front of a shock wave

to the values after the shock.

The density is also expressed as the specific volumes $V = 1/\rho$ and $V_0 = 1/\rho_0$ for the compressed and uncompressed cases, respectively

Uncompressed: P_0, E_0, ρ_0) are linked to values after the shock front compressed: P, E, ρ.

5. Determination of Cratering Parameters …

Hugoniot Equations …

- Initial pressure, energy, and density before the shock are known values, while the respective values after the shock are unknown quantities, as are the shock velocity U and particle velocity up behind the shock front. The Hugoniot equations are then written as:

$$\rho(U - u_p) = \rho_0 U$$
$$P - P_0 = \rho_0 u_p U$$
$$E - E_0 = (P + P_0)(V_0 - V)/2$$

where

$V = 1/\rho$ and $V_0 = 1/\rho_0$ are compressed and uncompressed specific (per unit mass) volumes,

ρ and ρ_0 are compressed and uncompressed densities,

E_0 and E are the specific internal energies; and P_0 and P are pressures in front of and behind the shock front.

5. Determination of Cratering Parameters ...

Hugoniot Equations ...

- U and u are the speeds, r e l a t i v e to the undisturbed medium, of the shock wave and the shock-compressed material, respectively. The symbols

  P, ρ, and E represent, respectively, the pressure, density, and s p e c i f i c

  internal energy of the material at the initial state (subscript 0) and at the shocked Hugoniot state (subscript H).

- For convenience, Eo may be chosen t o be zero;

  and since for hypervelocity impact two equations may be approximated as

  $P_H >> P_o$

5. Determination of Cratering Parameters …

Hugoniot Equations …

- The factors that effect the observed shock effect and consequently effect the Hugoniot equation- of-state of minerals and rocks are:
- initial volume of porosity
- grain size
- modal mineral composition
- shock impedance
- thermal conductivity of surrounding phases
- presence of voids
- water content

6. Hydrocode Modeling

- Hydrodynamic computer codes (hydrocodes) are powerful numerical tools for simulating the dynamics of continuous media.

- Several hydrocodes are developed from simple to complex impact cratering simulations involving phase changes and multiple materials.

6. Hydrocode Modeling …

Hydrocodes are developed to study various impact parameters such as

- viscous fluid flow
- elastic and plastic deformation
- tensile failure
- crater collapse
- dynamic fragmentation during an impact
- Spallation
- atmospheric breakup of meteoroids during atmospheric entry.

6. Hydrocode Modeling …

Examples of Hydrocode modeling programs:

- Earth Impact Effects Program:

  A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth

  G. S. Collins, H. J. Melosh, R. A. Marcus,

  Meteoritics & Planetary Science, 2005, v. 40, Nr. 6, 817–840.

- SALE 2 is an extensively modified version of SALE

  SALE : Simplified Arbitrary Lagrangian-Eulerian computer program,

  A. A. Amsden, H.M. Ruppel, C.W. Hirt,

  SALE: A Simplified ALE computer program for fluid flow at all speeds,

  Los Alamos National Laboratory Report LA-8095, 1980.

  C. E. Anderson Jr.,

  An overview of the theory of hydrocodes,

  International Journal of Impact Engineering, 1987, v. 5, 33-59.

6. Hydrocode Modeling ...

Energy of the impactor (meteorite)

$$E = (1/2)\, m_i v_0^2 = (\Pi/12)\rho_i L_0^3 v_0^2$$

- **L_0 is the impactor diameter at the top of the atmosphere,**
- **v_0 is the velocity of the impactor at the top of the atmosphere,**

Other necessary parameters are:

- **ρ_i is the impactor density,**
- **ρ_t is the target density,**
- **Θ is the angle subtended between the impactor's trajectory and the tangent plane to the surface of the Earth at the impact point**
- **r is distance from the impact site at which the environmental consequences are determined is measured along the surface of the Earth**
- **Δ isthe epicentral angle Δ between the impact point and this**
- **R_E is the radius of the Earth.**

distance r is given by $\Delta = r/R_E$

6. Hydrocode Modeling …

- a) the impactor of initial diameter L_0 begins to break up at a certain altitude; from then onwards because of different pressures on the front and back face the impactor spreads perpendicular to the trajectory.
- b) the impactor breaks up but the critical impactor diameter is not attained before the fragmented impactor strikes the surface.

Schematic illustration of two atmospheric entry scenarios considered in the Earth Impact Effects Program could be found in the reference.

6. Hydrocode Modeling …

Salient features of the Web program modeling of environmental effects of impact on Earth consists of

- Impact energy and recurrence interval
- Crater dimensions and melt production
- Thermal radiation
- Seismic effects
- Ejecta deposit
- Air blast
- Effect of water layer
- Global effects …

- Ref: Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth,

  G. S. Collins, H. J. Melosh, and R. A. Marcus,

  Meteoritics & Planetary Science 40, Nr 6, 817–840 (2005)

6. Hydrocode Modeling ...

- Melt volume produced during the impact event, based on the results of numerical modeling of the early phase of the impact event is studied by several authors.

  O'Keefe and Ahrens1982b,

  Grieve and Cintala 1992,

  Pierazzo et al. 1997,

  Pierazzo and Melosh, 2000,

- Assumptions are:

  1) the impact velocity is in excess of ~12 km s−1 (the threshold velocity for significant target melting, O'Keefe and Ahrens 1982b);

  2) the density of the impactor and target are comparable; and

  3) all impacts are vertical, these data are well-fit by the simple expression:

Interaction of matter under impact

" Matter is being accelerated very rapidly and,

the resulting stress wave will become a shock wave moving at supersonic speed (up to about 2/3 of the impact velocity).

Shock waves are inherently nonlinear and shock fronts are abrupt.

They can be mathematically represented as a discontinuous jump of pressure, density, particle velocity, and internal energy. In reality, shock waves have a finite thickness, up to a few meters in rocks, depending on their porosities."

Crater Dimensions and Melt production Modeling

- Determining the size of the final crater from a given impactor size, density, velocity, and angle of incidence is a complex task.
- The main difficulty in deriving an accurate estimate of the final crater diameter is that no observational or experimental data are present for impact craters larger than a few tens of meters in diameter.
- Hence modeling is required.
- Sophisticated numerical models capable of simulating
  - the propagation of shock waves,
  - the excavation of the transient crater,
  - the subsequent collapse

  are needed

6. Hydrocode Modeling ...

Laboratory experiments reveal that,

at low pressures and temperatures

(well below melting),

the yield strength of rock materials may be considered to have two components,

a cohesive strength that is independent of overburden pressure,

a frictional component that is a function of overburden pressure and, hence, depth.

(Lundborg, 1968).

The scaling laws are useful to extend the capabilities of the laboratory experiments.

6. Hydrocode Modeling ...

SCALING LAWS

A set of scaling laws that extrapolate the results of small-scale experimental data to scales of interest or extend observations of cratering on other planets to the Earth can be used.

The Scaling law is based on the works of Gault (1974), Holsapple and Schmidt (1982), Schmidt and Housen (1987), and combines a wide range of experimental cratering data such as small-scale hypervelocity experiments and nuclear explosion experiments

The equation relates the density of

- the target ρt and impactor ρi (in kg m−3),
- the impactor diameter after atmospheric entry L (in m),
- the impact velocity at the surface vi (in m s−1),
- the angle of impact θ (measured to the horizontal), and
- the Earth's surface gravity gE (in m s^{-2}).

7. Age Determination

A simple case:

Living bones contain U around 100 ppb (0.1 ppm).

Say we come across a fossilized tooth or bone

With U in that 1 – 15 ppm.

What does that mean?

7. Age Determination ...

- This means that bones and teeth are enriched in U during fossilization.
- U comes from ground water or interstitial water in archaeological layers.

Possible assumptions in the analysis

- The introduction of the U is effective shortly after death
- U is introduced continuously and slowly, then the analysis will have additional parameters to be considered.

7. Age Determination
Potassium – Argon Method

- Stable and radioactive isotope measurements provide excellent tools for the determination of age of an event or formation etc.
- Radioactive isotopes decay continuously at a constant rate.

This is expressed as

$N = N_o e^{-\lambda t}$

Where N is the number of parent nuclei existing at time t in terms of initial number of nuclei N_o .

Where λ is the decay constant

$= \ln 2/ T_{1/2}$.

$T_{1/2}$ = Half life of the radioisotope.

Ref: Montigny, R., The conventional Potassium-Argon Method, p. 295-321 in Nuclear Methods of Dating

7. Age Determination
Potassium – Argon Method …

$N_o - N = N(e^{-\lambda t} - 1)$

The value of t can be derived for a series of measurements of $(N_o - N)$

Radioactive isotopes for age studies may be distinguished into two types:

1) Primitive and 2) Cosmogenic

Primitive: radioisotopes that have existed since the formation of the Earth

^{147}Sm, ^{238}U

Cosmogenic: Continuously generated.

^{39}Ar, ^{14}C, ^{36}Cl

7. Age Determination
Potassium – Argon Method …

Principle:

^{40}K has a half life of $1.25x10^{9}$ years.

It decays by β decay 88.8% to ^{40}Ca and by electron capture 11.2% to ^{40}Ar.

Ref:

Nuclear Methods of Dating

E. Roth and B. Poty (Eds.)

Kluwer Academic Publishers Boston © 1989

ISBN 0-7923-0188-9

7. Age Determination
Potassium – Argon Method …

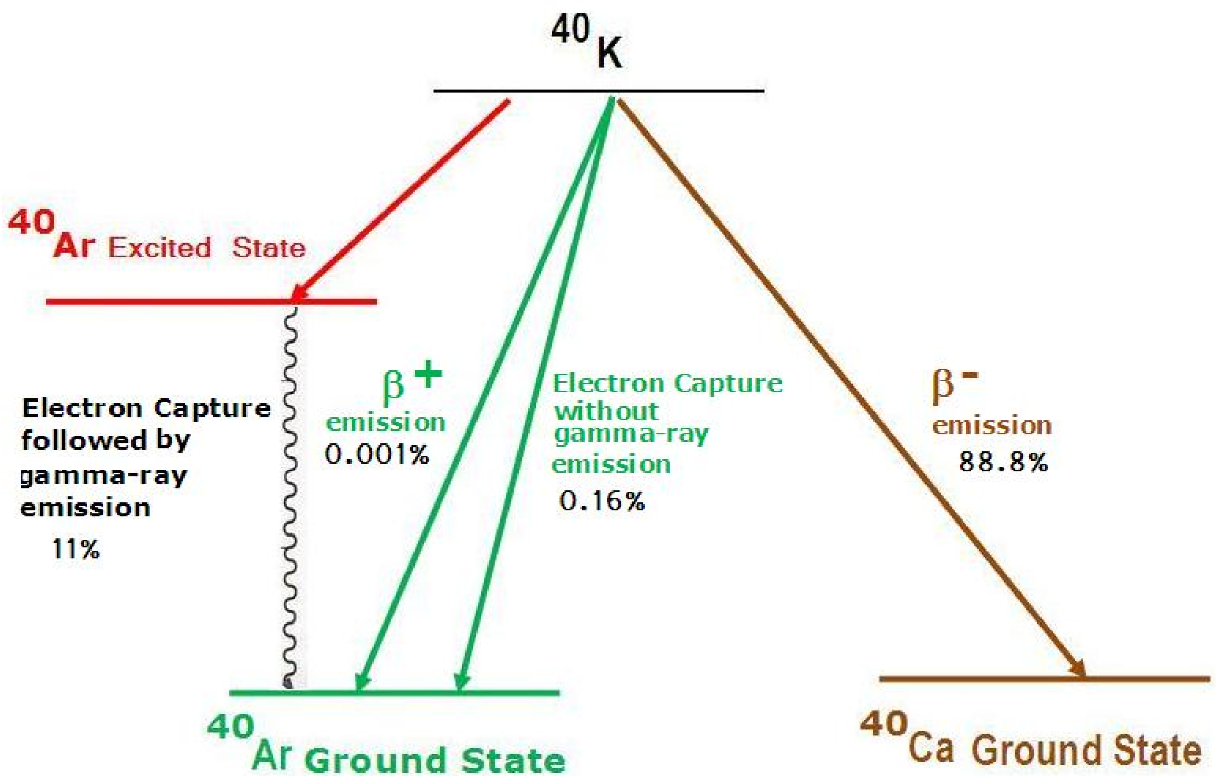
Review notes:

- During beta-minus decay, a neutron of the nucleus becomes a proton, an electron and an antineutrino.
- During beta-plus decay, a proton of the nucleus becomes neutron, a positron and a neutrino.
- Although the numbers of protons and neutrons in an atom's nucleus change during beta decay, the total number of particles (protons + neutrons) remains the same.

Electron Capture:

The process in which an atom or ion passing through a material medium either loses or gains one or more orbital electrons.

7. Age Determination Potassium – Argon Method …



Decay Scheme of ^{40}K

7. Age Determination
Potassium – Argon Method …

The age equation is given by

$$t = \frac{1}{\lambda\varepsilon + \lambda\beta} \log_e \left[\frac{^{*40}Ar}{^{40}K} \frac{\lambda\varepsilon + \lambda\beta}{\lambda\varepsilon} + 1 \right]$$

where

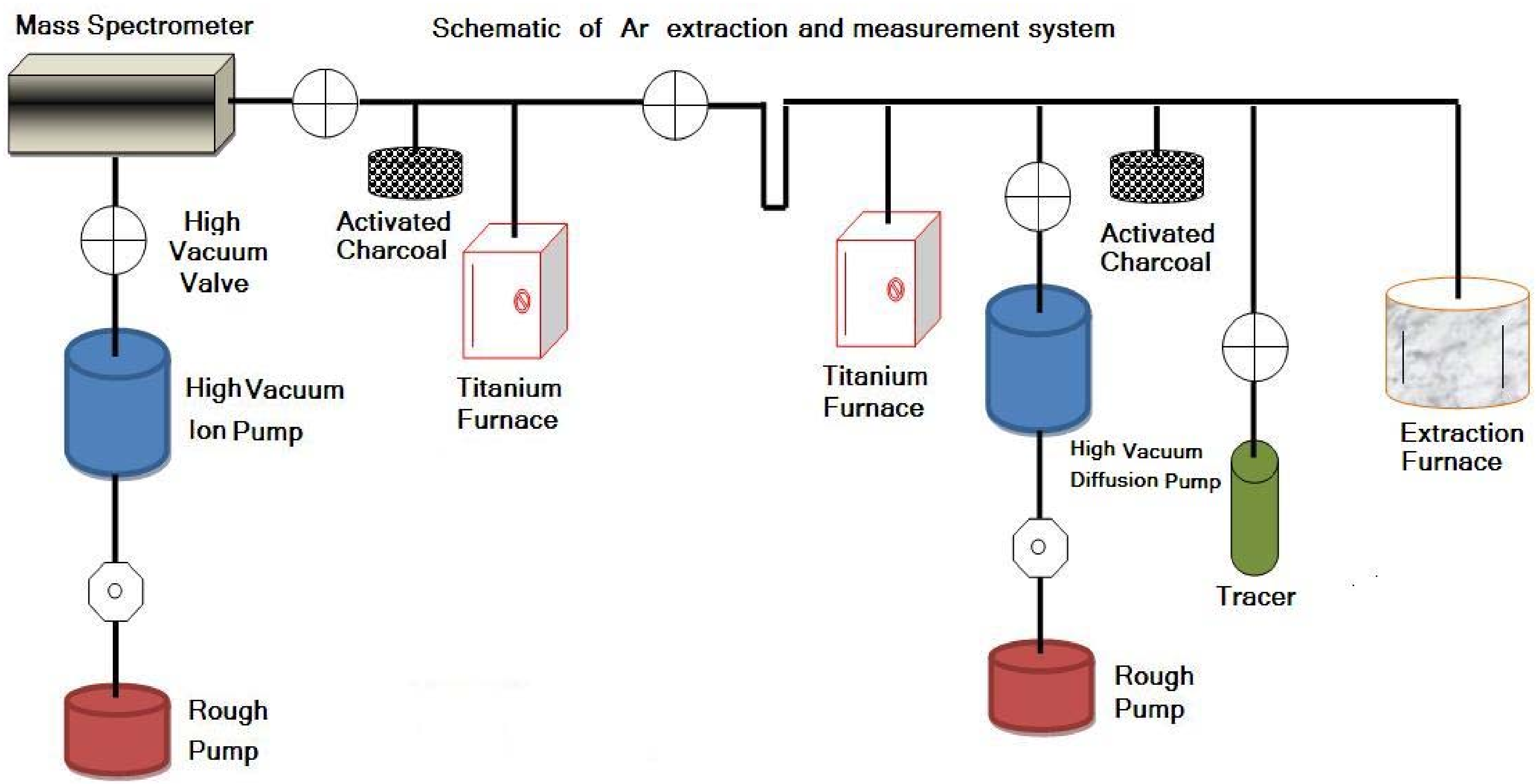
$\lambda\varepsilon$ refers to the decay of ^{40}K to ^{40}Ar

$\lambda\beta$ refers to the decay of ^{40}K to ^{40}Ca

$^{*40}Ar$ is radiogenic argon, produced by in situ decay of ^{40}K

For further details refer to
Montigny, R., The conventional Potassium-Argon Method, p. 297 inNuclear Methods of Dating

7. Age Determination
Potassium – Argon Method ...



Ref: Schematic is based on Figure 2, Montigny, R., The conventional Potassium-Argon Method, p. 299 in Nuclear Methods of Dating.

7. Age Determination
Potassium – Argon Method ...

- The analyzed argon consists of three components:

1) Radiogenic argon $^{40}Ar_{rad}$,
2) The trace Ar_T
3) Atmospheric contamination At_{atm}

The values of components Ar_T and At_{atm} are known, hence $^{40}Ar_{rad}$ can be calculated.

From this, the age of the sample can be calculated, (as shown in the next slide).

Ref: Montigny, R., The conventional Potassium-Argon Method, p. 300 in Nuclear Methods of Dating

7. Age Determination Potassium – Argon Method …

Argon Analysis is done currently by isotope dilution and mass spectrometry

The procedure consists of

1. A known amount of a rock or mineral is melted in a molybdenum crucible inserted in a high vacuum system.
2. When melting , a known amount of almost 99% enriched ^{38}Ar is added to gases extracted from the sample.
3. The mixture is purified by removal of oxygen, hydrogen, nitrogen and carbon dioxide.

7. Age Determination Potassium – Argon Method …

4. The rarefied gases are introduced into mass spectrometer
5. $^{40}Ar/^{38}Ar$ and $^{38}Ar/^{36}Ar$ are measured.
6. The fraction of atmospheric argon ^{38}Ar can be obtained from $^{38}Ar/^{36}Ar$ of the atmosphere.
7. $^{40}Ar/^{36}Ar = 295.5$ (known).
8. The radiogenic ^{40}Ar of the sample is calculated.
9. $^{40}Ar_{rad}$: number of ^{40}Ar atoms in the sample

   $^{38}Ar_T$: number of ^{38}Ar atoms of the tracer

   M means measured ratio;

   'a' means atmospheric ratio

7. Age Determination Potassium – Argon Method …

- Potassium Analysis:

K concentrations can be determined by one of the methods:

1) Flame spectrophotometry
2) Atomic Absorption
3) Neutron Activation
4) Isotope Dilution
5) Mass spectrometry

7. Age Determination
Potassium – Argon Method ...

$$t = \frac{1}{\lambda\varepsilon + \lambda\beta} \log_e \left[\frac{{}^{*40}Ar}{{}^{40}K} \frac{\lambda\varepsilon + \lambda\beta}{\lambda\varepsilon} + 1 \right]$$

decay constant of ^{40}K to ^{40}Ar

$\lambda\varepsilon = 0.581\mathrm{x}10^{-10}\ y^{-1}$

decay constant of ^{40}K to ^{40}Ca

$\lambda\beta = 4.962\mathrm{x}\ 10^{-10} y^{-1}$

Knowing all the parameters, namely, $^{*40}Ar$, ^{40}K, $\lambda\varepsilon$, $\lambda\beta$ on the right hand side of the equation, age of the sample can be determined.

Ref: Montigny, R., The conventional Potassium-Argon Method, p. 302 in Nuclear Methods of Dating

8. Neutron Activation Analysis

INTRODUCTION & CONCEPTS

Analytical technique is a tool to determine

- abundances of elements
- information about minerals
- information about organics

May be categorized as

- inorganic and organic
- qualitative and quantitative
- spectroscopic and classical

8. Neutron Activation Analysis …

INTRODUCTION & CONCEPTS …

- Qualitative means – identification.
- Quantitative means - determining the abundance.

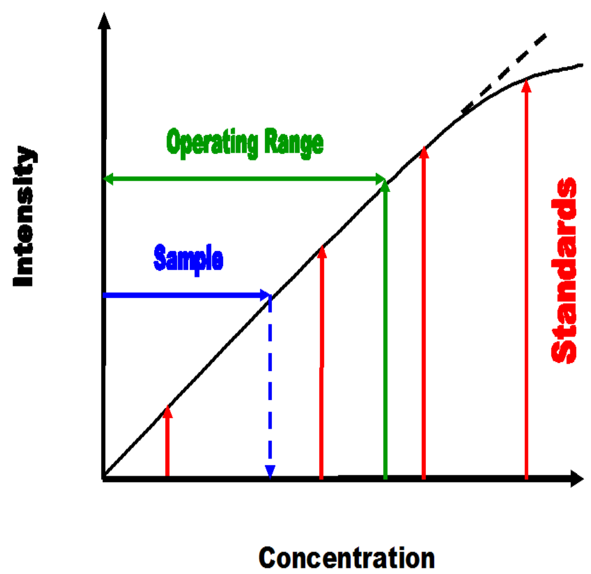
The basic concept of quantitative analysis:

Take a material, with known abundances, called the standard.

Using the known amount of abundance(s) in the standard, estimate the abundance(s) in the unknown called the sample, maintaining all the conditions and parameters same for the the sample and the standard.

CALIBRATION CURVE

Quantitative analysis involves determination of a calibration curve by measuring the analytical signal as a function of known concentrations of the standard(s), conducted in a range of values.



Calibration curve for quantitative analysis

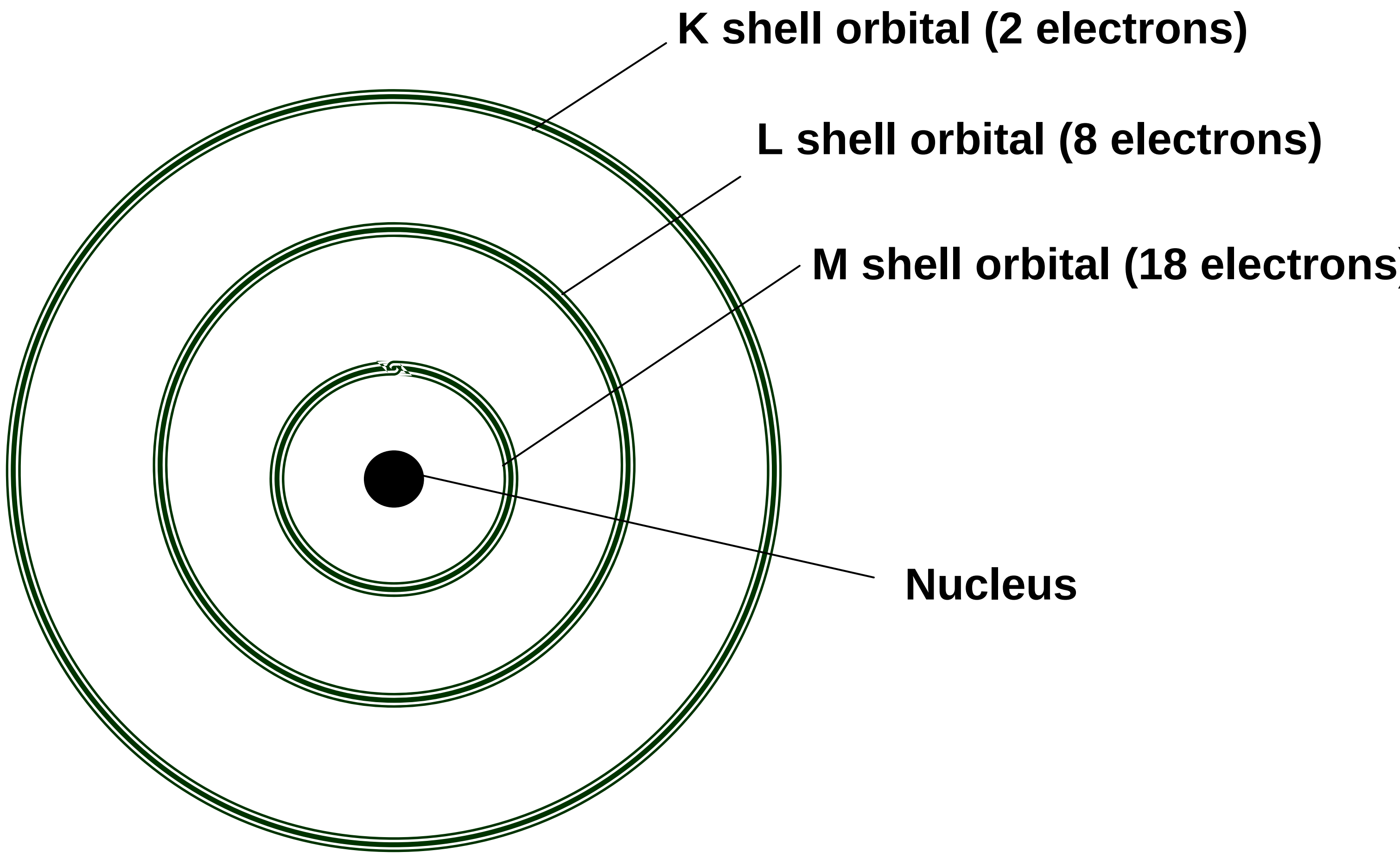
8. Neutron Activation Analysis ...

SPECTROSCOPIC TECHNIQUES ...

- The different energies of the photons in the electromagnetic spectrum are representative of different types of interactions in the atoms and molecules; and are detected and measured by different types of spectroscopic techniques.
- Microwave and infrared spectroscopy use the properties of molecular **rotations and vibrations**.
- Ultra violet and visible light spectroscopy utilize **absorption** and **emission** of energies of outer electron transitions.
- X-ray **fluorescence** – inner electrons
- Gamma rays – **nuclear transitions**.

8. Neutron Activation Analysis …

PICTORIAL DEPICTION OF ATOMIC NUCLEUS – ELECTRON ORBITALS



Neutron irradiation

- A stable isotope when bombarded with neutrons, absorbs a neutron; and by the most common type of nuclear reaction, namely, (n, gamma) reaction, gets transformed into higher mass unstable nucleus.

$$ {}^{A}_{Z}X_{N}\ (n,\gamma)\ X^{*}\ (\text{unstable})\qquad {}^{A+1}_{Z}X_{N+1} $$

- When the unstable nucleus de-excites by prompt gamma rays, and gets transformed into a radioactive nucleus (with next higher neutron number). This radioactive nucleus decays mainly by beta rays and (or) characteristic gamma-rays.

Nuclear Reaction

Nuclear reaction occurs when target nuclei are bombarded with nuclear particles, depicted pictorially

$$X + a \longrightarrow Y + b + Q$$

Or

X(a,b)Y

Target X is bombarded by particle "a",

Y is the product nuclei with resulting particle "b" .

Q is the energy of the nuclear reaction, which is the difference between the masses of the reactants and the products.

Ex:

$$^{59}_{27}Co_{32} + {}^{1}_{0}n_{1} \longrightarrow {}^{60}_{27}Co_{33} + \gamma$$

or

$$^{59}_{27}Co_{32}\ (n, \gamma)\ {}^{60}_{27}Co_{33}$$

ANALYSIS OF SOLIDS BY NEUTRON ACTIVATION ANALYSIS (NAA) AND GAMMA SPECTROSCOPY

Principle:

Neutron Activation Analysis is a nuclear analytical technique that involves irradiating a sample with neutrons. The stable isotopes of different elements in the sample become radioactive. The radioactivity of different radionuclides can be detected and quantified by gamma spectroscopy.

8. Neutron Activation Analysis …

- **Neutron capture**:

  The target nucleus absorbs (captures) a neutron resulting in a product isotope, the mass number of which is incremented by one. If the product nucleus is unstable, it usually de-excites by emission of gamma rays and/or β.

- Ex:

$$ {}^{58}_{26}\mathrm{Fe}_{32} \quad (n, \gamma) \quad {}^{59}_{26}\mathrm{Fe}_{33} \quad . $$

8. Neutron Activation Analysis …

GAMMA SPECTROMETER

- An irradiated material is radioactive emitting radiations – α, β, γ, ………
- For Neutron Activation Analysis – usually gamma radiation is selected.
- **Gamma spectrometer** is the detection system that measures gamma ray intensity**.**

8. Neutron Activation Analysis ...

SPECTROMETER

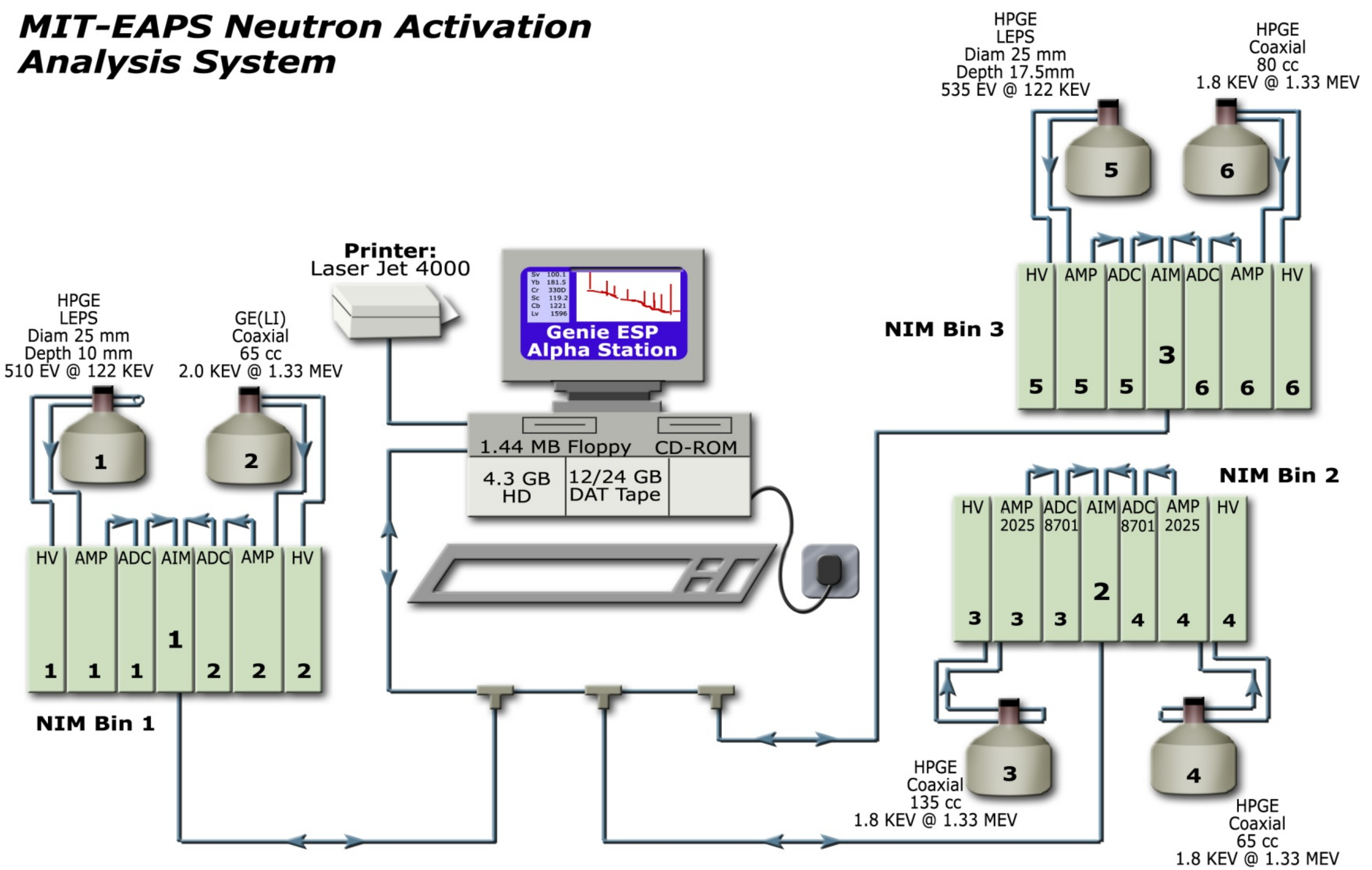
Gamma spectrometer system for measuring the gamma-ray activity of an irradiated material consists typically

1) Detector
2) Amplifier
3) Multi Channel Analyzer
4) Computer & peripherals

This is shown pictorially in the next slide.

8. Neutron Activation Analysis …

Gamma Spectroscopy System



8. Neutron Activation Analysis ...

GAMMA DETECTOR...

The energy of nuclear radiation is converted into an electrical signal by a device that is the nuclear radiation detector.

The three major categories of gamma detectors used in Neutron Activation Analysis are:

1)Scintillators : NaI(Tl), CsF, ZnS(Ag)

2)Semiconductors : Si, Ge, CdTe, GaAs

3)Gas Filled : He, Air, H_2, N_2

8. Neutron Activation Analysis ...

GAMMA DETECTOR...

- The nuclear radiations emanating from the irradiated material will cause ionization in the detector medium by means of charged particle products of their interactions.

- The scintillators and the semiconductors have energy discrimination capacity better than the gas filled detectors.

GAMMA DETECTORS...

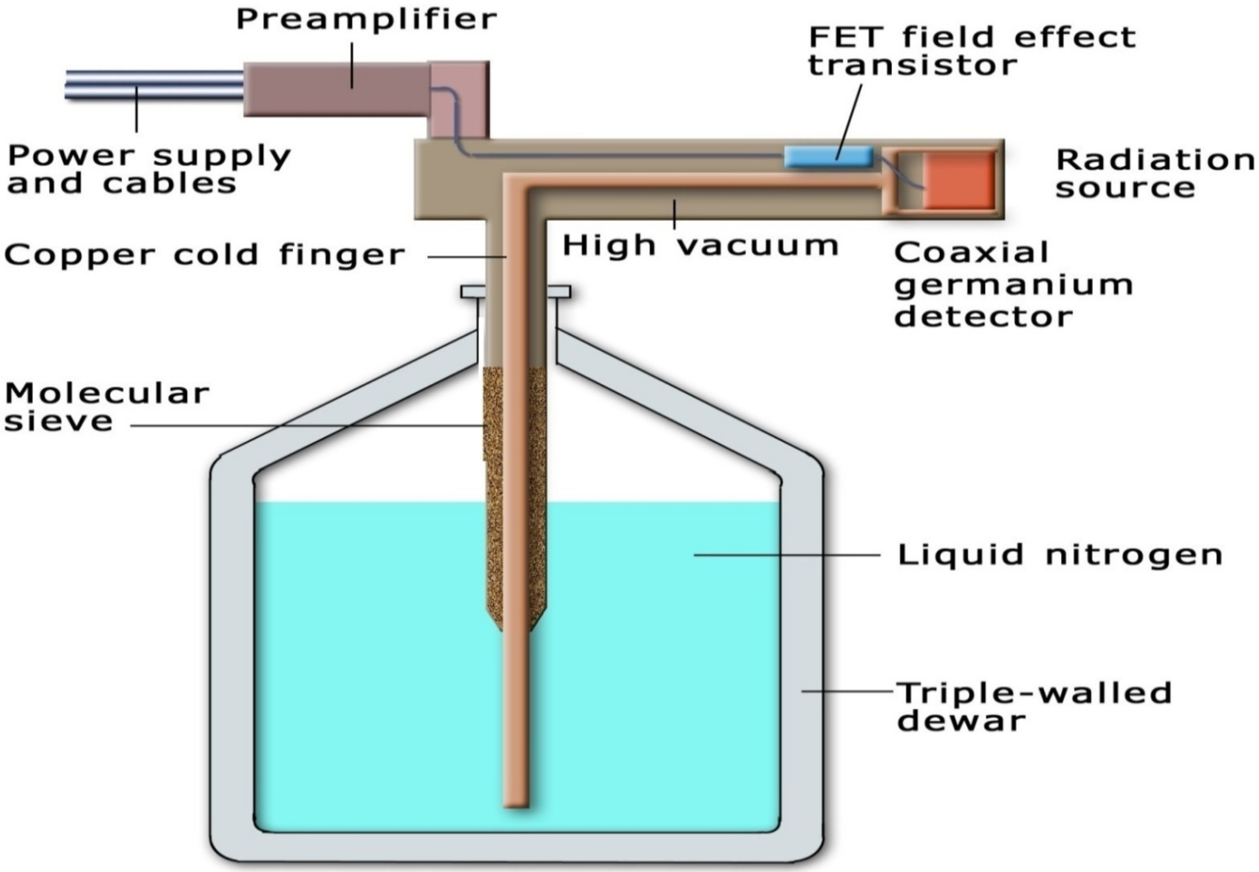
The nuclear radiations incident on the detector crystal initiate ionizations by creation of electrons (negative charge) and holes (positive charge).

An electric field is created by applying high voltage to the electrodes mounted on opposite sides of the detector crystal. The charge carriers get attracted to the electrodes of opposite polarity because of the electric field. The charge collected at the electrodes is proportional to the energy lost by the incident radiation.

A germanium detector system and a typical gamma spectrum are shown in the next two slides

8. Neutron Activation Analysis …

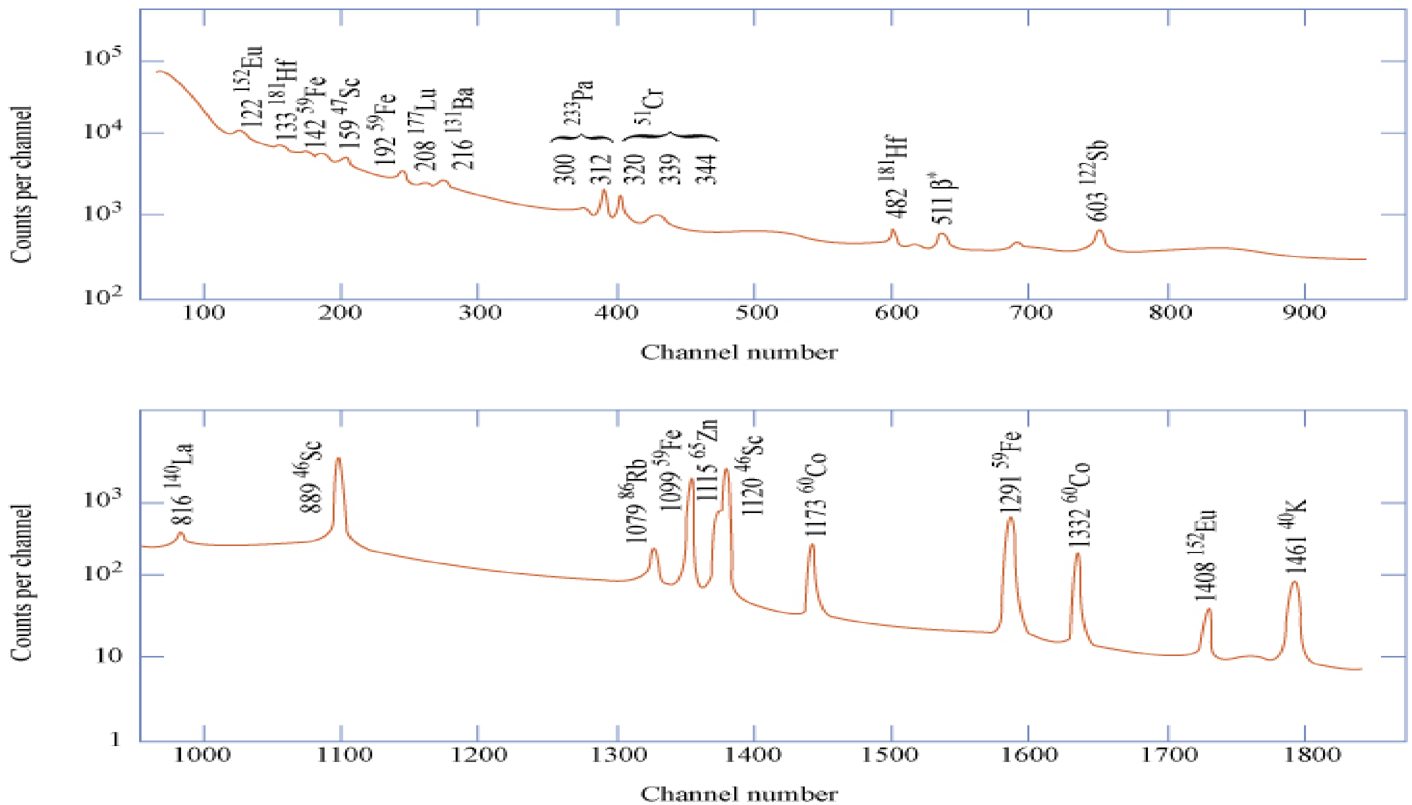
Components of a Germanium Detector System



Ref: Knoll, G. F., Radiation detection and measurements.
Debertin, K., and Helmer, R. G.,
Gamma and X-ray spectrometry with semiconductor detectors

8. Neutron Activation Analysis ...

Typical Gamma-ray Spectrum of Irradiated Cayenne after a Delay of 10 d



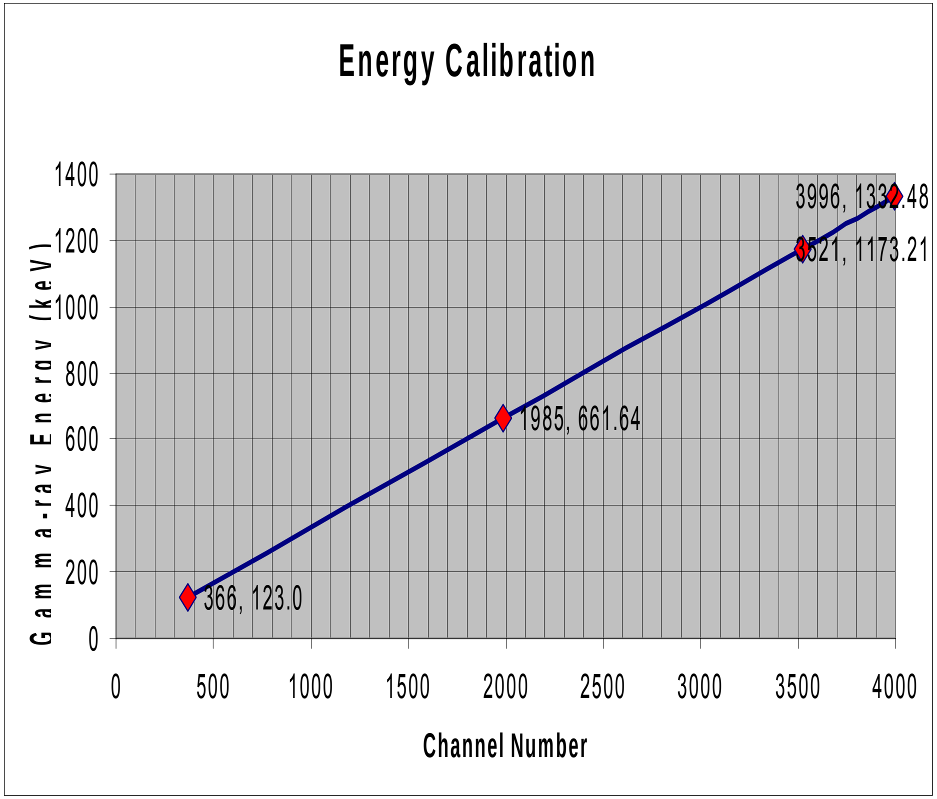
After P. ILA, P. JAGAM: Multielement Analysis of Food Spices

Ref: P. Ila and P. Jagam, Journal of Radioanalytical and Nuclear Chemistry, 57 (1980) 205-210.

8. Neutron Activation Analysis ...

Energy Calibration of a Gamma Spectrometer using Standard Calibration Sources

Source	Gamma-ray Channel Number	Energy keV
^{57}Co	123.0	366
^{137}Cs	661.64	1985
^{60}Co	1173.21	3521
	1332.48	3996



COMPARATOR METHOD

- **AStandard = Activity of an isotope of an element in the known (Standard) is proportional to the amount present.**
- **ASample = Activity of the isotope of the same element in the unknown (Sample)**
- **AmountStandard/ AmountSample**

  = AStandard / Asample
- **AmountSample = AmountStandard * AStandard / Asample**

  assuming all the values of standard and sample are normalized to the same experimental conditions.

8. Neutron Activation Analysis ...

Trace Element Analysis of Impact Melt Rocks
Instrumental Neutron Activation Analysis

	C1-N10-1		Y6-N19-P			C1-N10-1		Y6-N19-P	
	ppm	Error ppm	ppm	Error ppm		ppm	Error ppm	ppm	Error ppm
Sc	16.6	0.2	12.4	0.1	La	21.9	0.3	23.3	0.3
Cr	88	1	114	2	Ce	45.2	0.5	36.8	0.5
Co	16.2	0.2	9.8	0.1	Nd	26	3	16	2
Ni	30	8	20	8	Sm	4.53	0.07	3.05	0.04
As	0.7	0.2	0.4	0.1	Eu	1.04	0.02	0.69	0.01
Se	<0.4		<0.3		Tb	0.72	0.01	0.42	0.01
Br	3.1	0.3	1.2	0.1	Yb	2.69	0.04	1.71	0.03
Rb	55	2	67	3	Lu	0.41	0.01	0.27	0.006
Sr	336	18	640	30	Hf	3.84	0.06	2.61	0.05
Zr	155	18	98	19	Ta	0.62	0.02	0.35	0.01
Sb	0.11	0.01	0.22	0.01	W	1.1	0.4	1.7	0.3
Cs	0.16	0.02	0.33	0.02	Ir (ppb)	6.0	0.7	<1.6	
Ba	701	17	745	17	Au (ppb)	40	2	17	1
					Th	7.18	0.08	6.9	0.1
					U	2.0	0.1	3.05	0.09

Ref: Schuraytz et al (Geology, 1994, v. 22, p. 871, NASA-CR-203591)

9. Inductively Coupled Plasma Emission Spectroscopy

ICPMS technique is useful for multi-element analysis of geological, environmental and medical sample materials.

ICPMS provides information about the abundances as well as isotopic ratios of the nuclides.

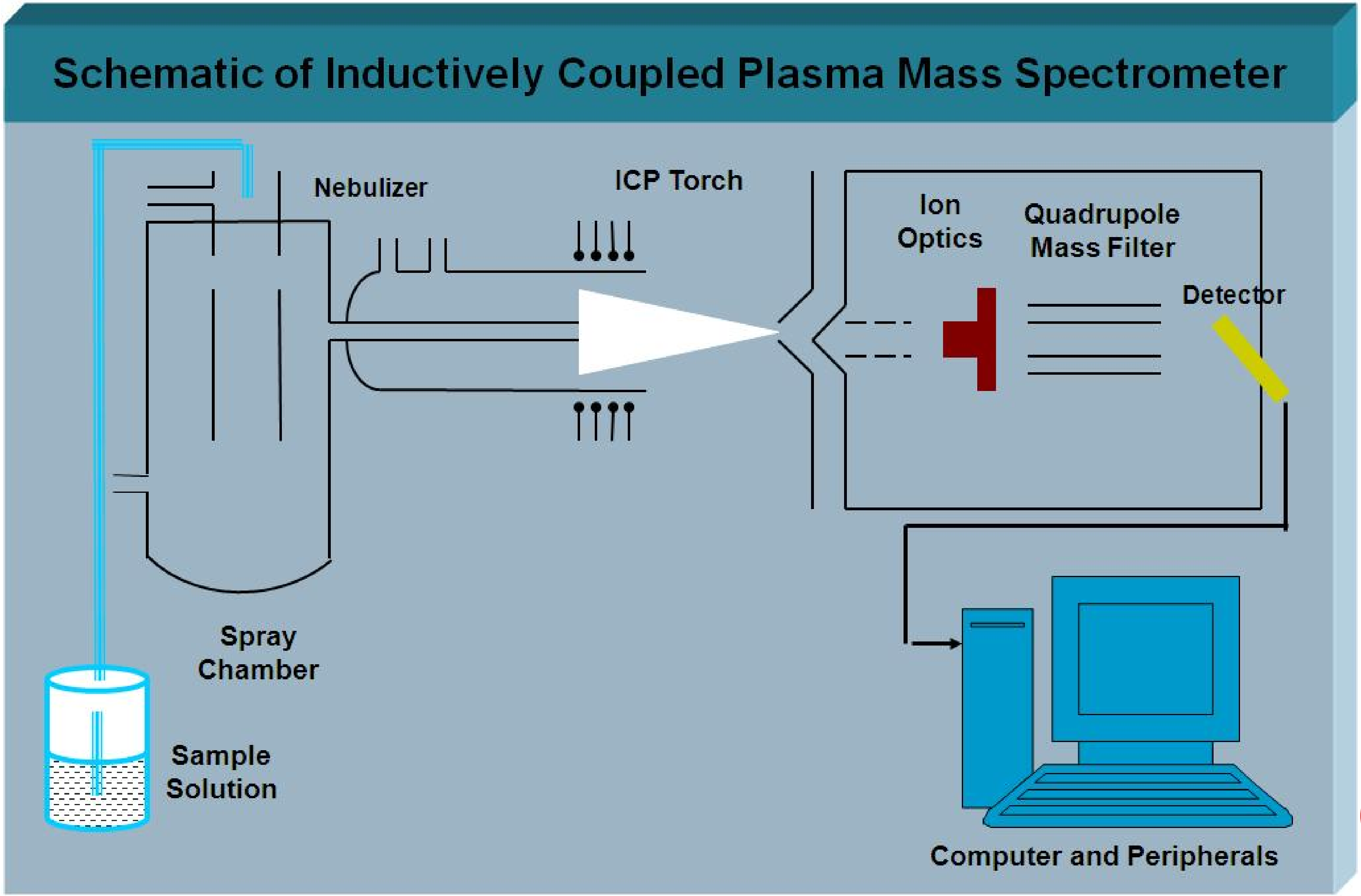
9. Inductively Coupled Plasma Emission Spectroscopy

Principle:

- The ICPMS technique consists of a high temperature plasma, into which the sample aerosol is injected and positively charged ions

  are generated by the interaction.
- A mass spectrometer quantifies the ionization based on the mass to charge ratio.
- Knowing the concentration of an element (of corresponding isotope) in the standard, the unknown concentration in the sample is calculated.

9. Inductively Coupled Plasma Emission Spectroscopy



Ref: P. J. Potts, Handbook of silicate Rock Analysis

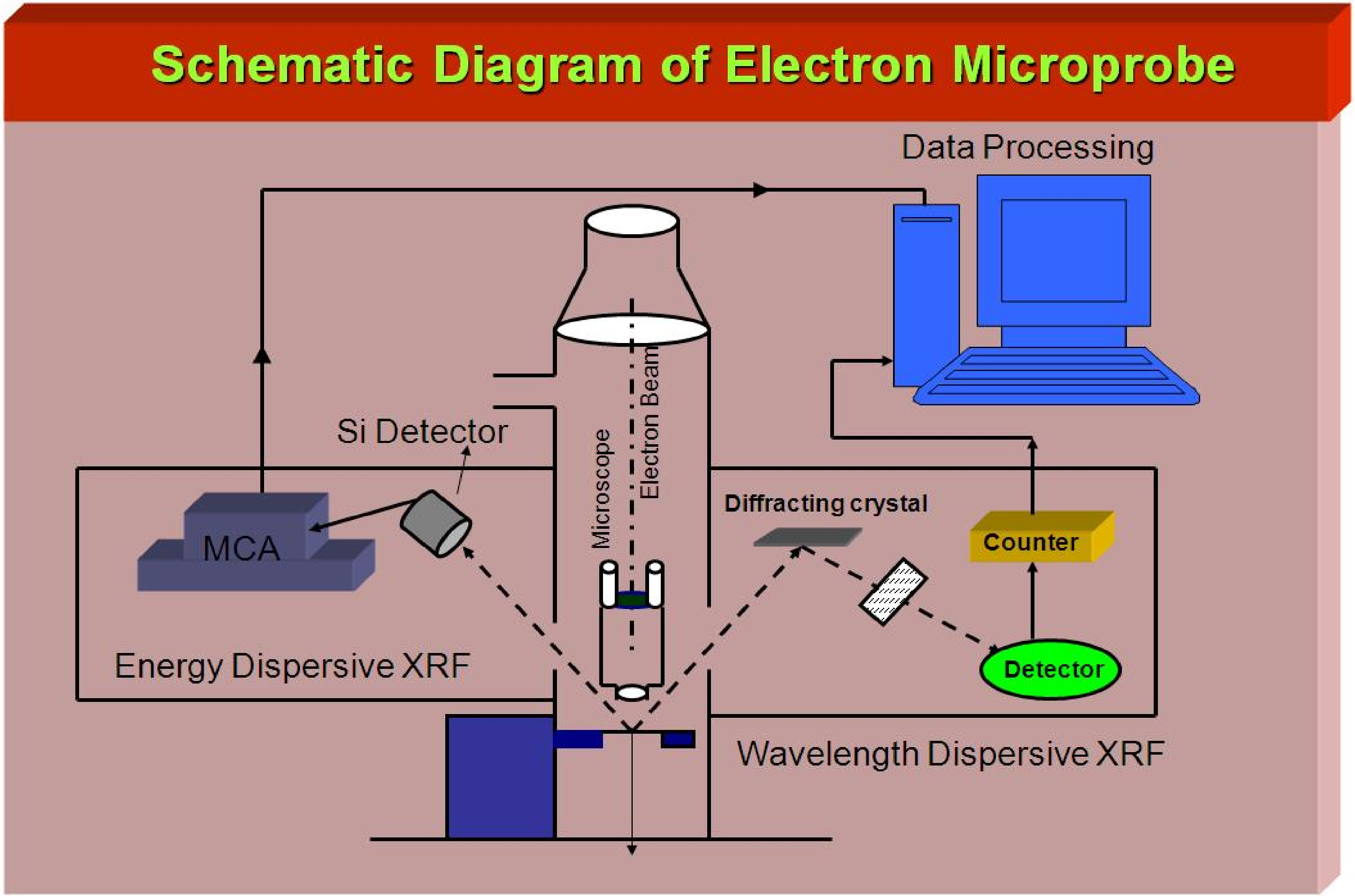
10. Electron Microprobe Analysis

- Electron probe microanalysis technique is useful to analyze the composition of a selected surface area of diameter size of few microns (micron = 0.001 meter = 0.1 cm) of the sample.
- For example in geological materials – can determine
  - composition of individual minerals
  - variation of concentration within a single grain
- For this type of analysis – the samples are to be polished thin sections mounted

  in a resin block, or

  glass slide backing.

10. Electron Microprobe Analysis …



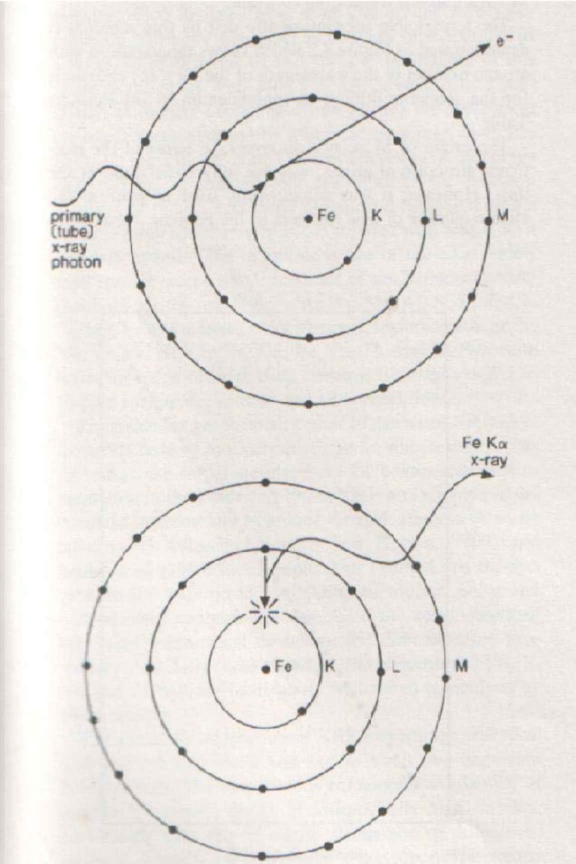
Ref: P. J. Potts, Handbook of Silicate Rock Analysis

10. Electron Microprobe Analysis …

WAVELENGTH DISPERSIVE XRF (WDXRF)
ENERGY DISPERSIVE XRF (EDXRF) …

Principles:

- In a stable atom, electrons occupy in discrete energy orbitals; the notation of these orbitals in decreasing binding energy level is K, L, M, … .
- The sample is excited by means electromagnetic radiation generated by radioisotopes, X-ray tubes, charged particles (electrons, protons and alpha particles).
- WDXRF use X-ray tubes
- EDXRF uses both X-ray tube and radio-isotopes.



Schematic representation of the mechanism of x-ray fluorescence of an iron atom leading to the emission of an Fe $K\alpha$ x-ray.

WAVELENGTH DISPERSIVE XRF (WDXRF)
ENERGY DISPERSIVE XRF (EDXRF)

- Dispersive means separation and measurement.
- WDXRF – Separation is done by collimators and diffraction crystals. Measurement is done by detecting the characteristic wavelengths by scintillation detectors and proportional counters providing a pulse height distributed spectrum.
- EDXRF – the wavelength dispersive crystal and detector system is replaced by solid state energy dispersive system consisting of Si(Li) detector coupled to a Multichannel analyzer system.

10. Electron Microprobe Analysis ...

Major Element Analysis of Impact Melt Rocks
Electron Microprobe Analysis

	C1-N10-1		Y6-N19-P	
	%	Error %	%	Error %
SiO_2	64.4	0.40	61.7	0.50
TiO_2	0.53	0.02	0.36	0.01
Al_2O_3	14.9	0.20	13.7	0.10
FeO	4.60	0.10	3.83	0.02
MnO	0.09	0.01	0.08	0.01
MgO	2.76	0.07	2.55	0.02
CaO	5.50	0.10	10.01	0.09
Na_2O	3.71	0.05	2.54	0.02
K_2O	2.72	0.03	2.27	0.03
P_2O_3	0.13	0.01	0.09	0.01
SO_3	0.07	0.01	0.08	0.01
Sum	99.4		97.2	

Ref: Schuraytz et al (Geology, 1994, v. 22, p. 871, NASA-CR-203591)

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