지구물리 공학

Introduction

지구물리학

- 정의
  - 지구물리학(Geophysics)이란?
    - 이름으로부터: 지구 + 물리 →

    - 기초학문: 지질학, 물리학, 화학
    - 지구와 지구를 구성하는 재료들인 물질과 에너지 특성을 연구하는 과학

  - 넓은 의미의 지구물리학

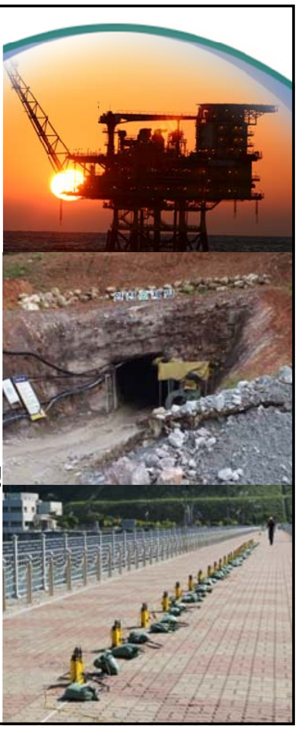
  - 일반적으로 받아들여지는 지구물리학

고체지구물리학

- 분류
  - 연구목적에 따른 분류
    - 순수 지구물리학 (pure geophysics)

    - 응용 지구물리학 (applied geophysics) 또는 물리탐사

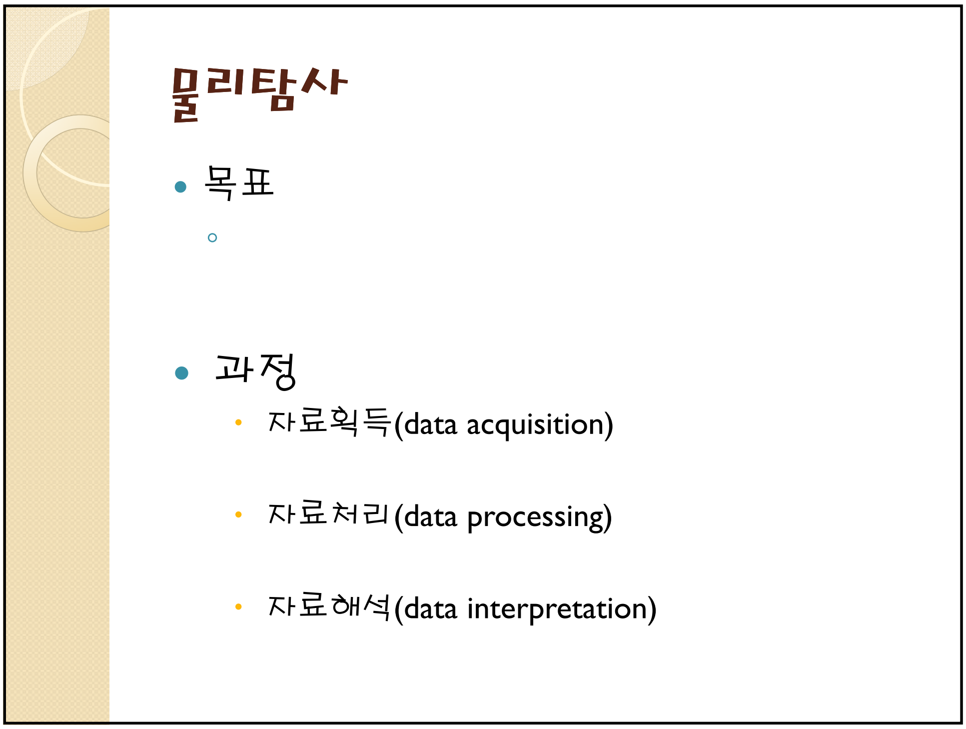
물리탐사



- 목적 및 활용분야
  - 에너지자원탐사
    - 석유, 가스, 메탄가스하이드레이트
    - 유용광물자원탐사 (금속광상탐사)
    - 지열탐사

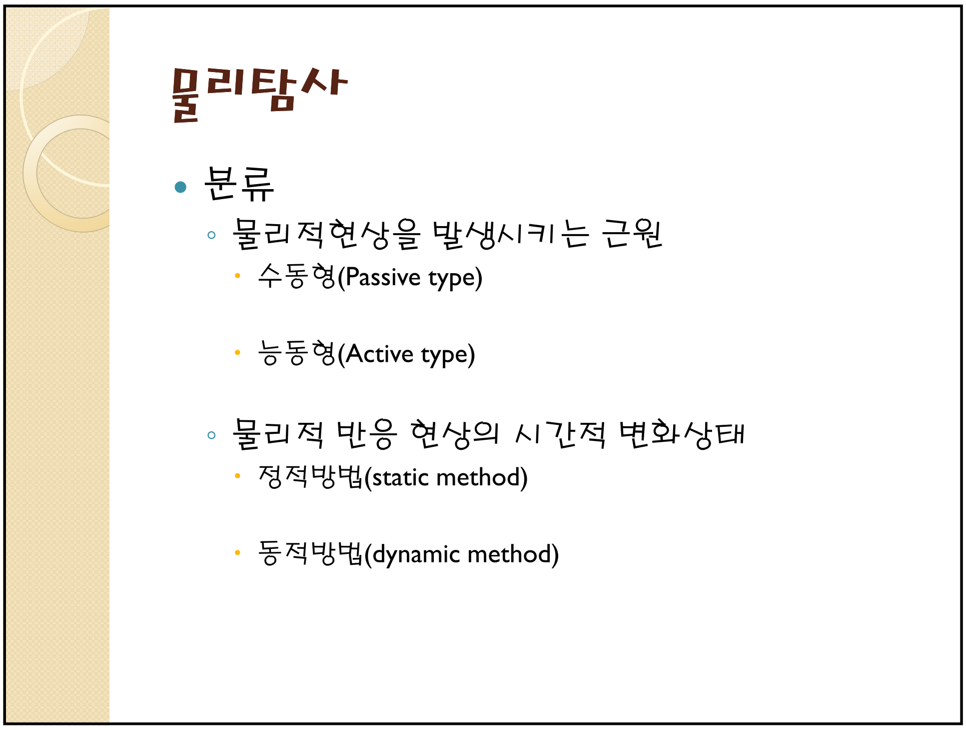
  - 토목 건축분야의 지반조사 및 안정성 평가
    - 건설을 위한 부지선정 (CO2부지선정
    - 댐, 건축물 등의 안정성 평가

  - 환경탐사
    - 지하수 오염 및 모니터링



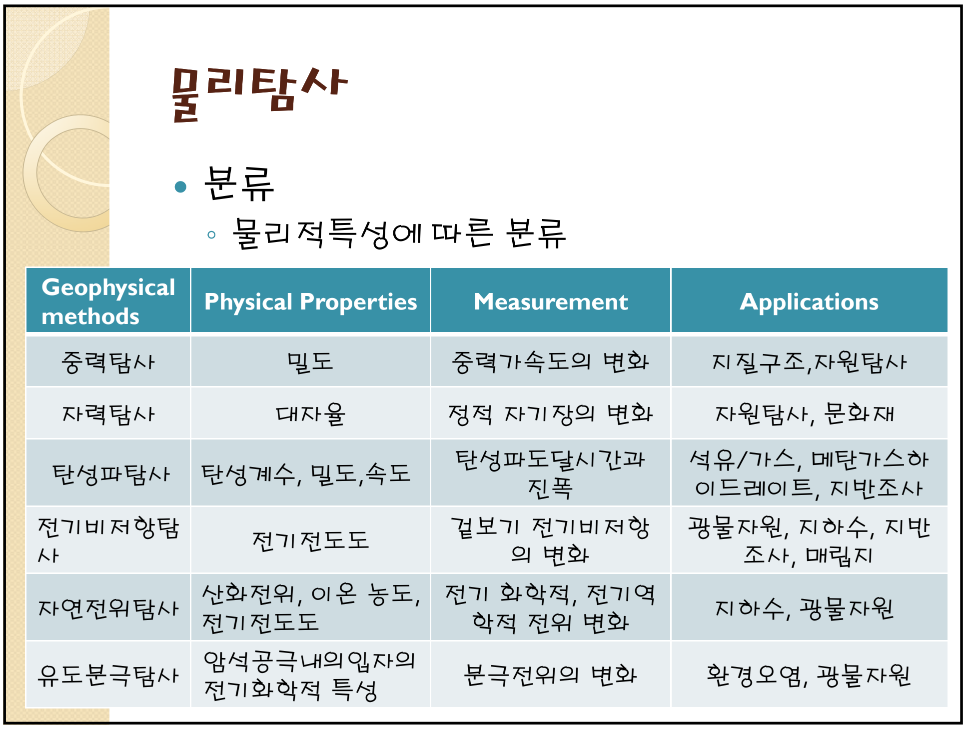
물리탐사

- 목표
- 과정
  - 자료획득(data acquisition)
  - 자료처리(data processing)
  - 자료해석(data interpretation)



물리탐사

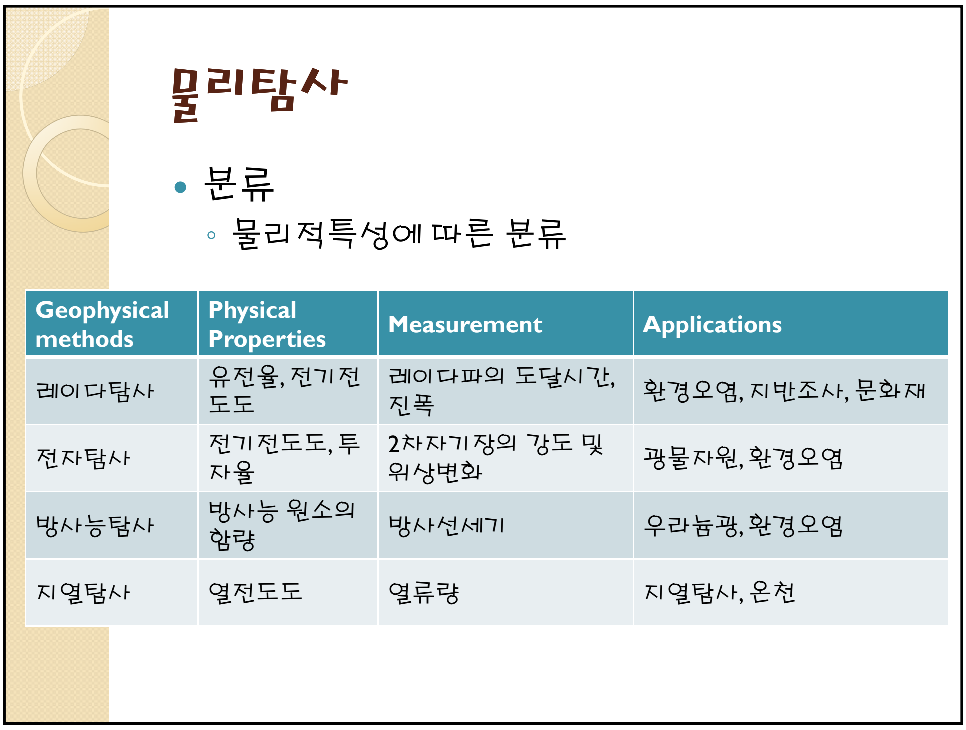
- 분류
  - 물리적현상을 발생시키는 근원
    - 수동형(Passive type)
    - 능동형(Active type)
  - 물리적 반응 현상의 시간적 변화상태
    - 정적방법(static method)
    - 동적방법(dynamic method)



물리탐사

- 분류
  - 물리적특성에 따른 분류

Geophysical methods	Physical Properties	Measurement	Applications
중력탐사	밀도	중력가속도의 변화	지질구조,자원탐사
자력탐사	대자율	정적 자기장의 변화	자원탐사, 문화재
탄성파탐사	탄성계수, 밀도,속도	탄성파도달시간과 진폭	석유/가스, 메탄가스하이드레이트, 지반조사
전기비저항탐사	전기전도도	겉보기 전기비저항의 변화	광물자원, 지하수, 지반조사, 매립지
자연전위탐사	산화전위, 이온 농도, 전기전도도	전기 화학적, 전기역학적 전위 변화	지하수, 광물자원
유도분극탐사	암석공극내의입자의 전기화학적 특성	분극전위의 변화	환경오염, 광물자원



물리탐사

- 분류
  - 물리적특성에 따른 분류

Geophysical methods	Physical Properties	Measurement	Applications
레이다탐사	유전율, 전기전도도	레이다파의 도달시간, 진폭	환경오염, 지반조사, 문화재
전자탐사	전기전도도, 투자율	2차자기장의 강도 및 위상변화	광물자원, 환경오염
방사능탐사	방사능 원소의 함량	방사선세기	우라늄광, 환경오염
지열탐사	열전도도	열류량	지열탐사, 온천

물리탐사

- 분류
  - 탐사위치에 따른 분류
    - 육상물리탐사
    - 항공물리탐사
    - 해상물리탐사
    - 시추공물리탐사

중력탐사

Gravity method

서론

- 중력탐사란
  - Gravity method, Gravity prospecting
  - Measure variations in the gravitational field of the earth
    → (중력이상, gravity anomaly   )
    (지구중력장의 변화량을 측정, 10^8분의 1까지 측정)
  - 육상, 해양, 항공탐사 가능
  - Natural source이용 → (passive   ) method
  - 중력탐사에서 다루는 물성: (density   )
  - 지구중력장에 비해 (밀도)변화에 의해 나타나는 중력이상은 매우 작음 → Sensitive instruments are needed.

서론

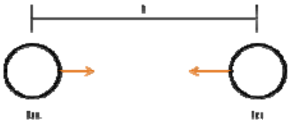
- 중력탐사활용
  - 중력탐사로부터 얻는 구조는? (광역적인 구조   )
    - 고정밀 중력탐사
  - 기반암(basement)의 분포, 퇴적분지의 분포 (두께 등)
  - 모든 지구물리조사연구에서 기초자료로 활용
    - Reconnaissance (preliminary) tool in oil exploration
    - Considerably cheaper than the seismic method.
    - Secondary method in mineral exploration

서론

- 중력탐사의 적용분야
  - 탄화수소탐사
  - 광역적인 지질연구
  - 지각평형보정
  - 광물광상의 탐사 및 매장량 평가
  - 지하공동의 탐지(고정밀 중력탐사)
  - 매몰 암석계곡의 위치파악(지하수탐사)
  - 빙하두께 결정
  - 조석진동(tidal oscillation)
  - 고고지구물리학(고정밀 중력탐사): 고분위치탐사등
  - 지구의 모양(측지학)
  - 화산활동 감시

기초이론

- Newton's law of gravitation
  - Gravitational force: the force between two particles of mass m_1 and m_2 is directly proportional to the product of the masses and inversely proportional to the square of the distance between the centers of mass



$F = G\frac{m_1 m_2}{r^2}$ →scalar

$\mathbf{F} = -G\frac{m_1 m_2}{r^2}\mathbf{r}_1$ →vector

  - Acceleration of gravity
    - if m_1 is the mass of the earth M_e and R_e is the radius of the earth: The acceleration of $m_2 = \frac{F}{m_2} = -G\frac{m_1}{r^2}\mathbf{r}_1$
    - At the earth's surface: $\mathbf{g} = G\frac{M_e}{R_e^2}\mathbf{r} = 980 cm/\sec^2 = 980 gal$
    - The unit of acceleration of gravity 1 cm/sec^2 (gal)

기초이론

- Gravitational potential
  - Definition:The potential at a point in a given field is defined as the work done by the force in moving a unit mass from an arbitrary reference points (usually at an infinite distance) to the point
  - The work needed to move the unit mass for a distance ds $dW = \mathbf{F} \bullet \mathbf{ds} = F \bullet ds \cdot \cos\theta = F \cdot dr$
  - Potential & Path: potential은 path에 무관하다.
  - Acceleration & Potential

$$\mathrm{U} = W = \int dW = \int_{\infty}^{R} F dr = G m_1 \int_{\infty}^{R} -\frac{dr}{r^2} = \frac{G m_1}{R}$$

$$g = \frac{\partial U}{\partial r} = \nabla U = -\frac{G m_1}{r^2}$$

  - Equipotential Surface

: Any surface along which the potential is constant is referred to as on equipotenial surface
→등포텐셜면을 따라 움직이는 물체는 일을 하지 않는다.

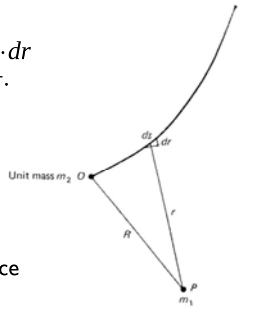


FIGURE 12-1 Gravitational potential is the work done by the attractive force of m_1 on m_2 as it moves to O from infinity.

기초이론

- Gravitational potential in 3 dimension
  - Potential due to an element at a distance r from P

$$dU = G\frac{dm}{r} = G\frac{\rho}{r}dxdydz$$

$$U = \int dU = G\rho\iiint\frac{1}{r}dxdydz$$

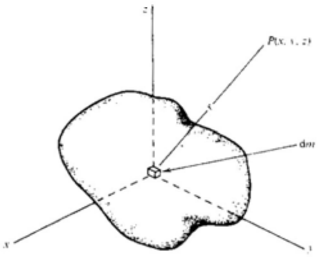


Fig. 2.1 Potential of three-dimensional mass.

지구의 형상 (figure of the earth)

- Spheroid

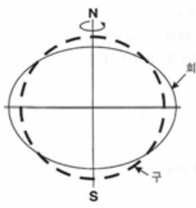


그림 2.1 구와 회전타원체의 차이를 확대한 그림

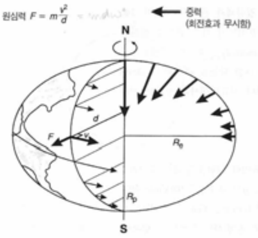


그림 2.3 원심력과 위도 φ에 따른 중력의 변화

  - Earth’s radius

극지방 6357km

적도 6378km

  - The observed gravity

= 중력 + 원심력

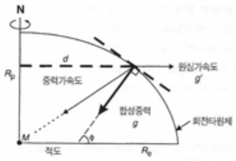


그림 2.4 원심가속도(g')와 중력가속도(g)의 합성력(실제 크기가 아님). 지리위도(geographic latitude)는 φ이다(Robinson과 Coruh, 1988).

지구의 형상 (figure of the earth)

- 지구타원체 (회전타원체, reference spheroid)
  - 지표면에서의 중력값을 수학적으로 표현하기 위해 가정된 지구의 형상
  - Basic assumption: the earth rotates about its polar axis and its density increases with depth, for example, from 3 g/cm^3 to 12 g/cm^3 . There is no lateral variation in density
  - Equipotential surface이며, 지구중력에 수직인 면
  - 그러나 실제 equipotential surface는 지구타원체와는 다름
  - The international formula adopted by IAG (International Association of Geodesy) in 1971 is

지구의 형상 (figure of the earth)

- 지오이드 (Geoid)
  - Practical mean sea level (equipotential surface)
  - In the ocean: it is defined as average sea level
  - On land: it is defined as average seal level over the surface of sea water in virtual canals which cut through the land masses.

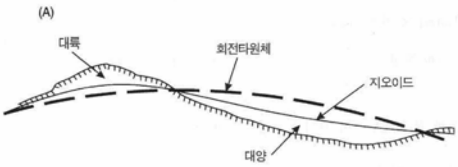


그림 2.2 지오이드의 변화.
(A) 광역적 효과

  - If there is excess mass:

중력이상의 계산

- 중력탐사
  - 중력탐사의 목표: 중력가속도의 변화량(중력이상)탐지
  - 그림 2-1: 지표면상의 점 P에서 지하 광체에 의한 중력가속도 변화량 측정

$$\text{지구중심방향의 중력가속도} = \frac{Gdm}{r^2} \cdot \sin\theta$$

$$dm = (\rho_2 - \rho_1)dV = \sigma \cdot dV$$

$$\therefore \Delta g = G\sigma \iiint \frac{\sin\theta dV}{r^2}$$

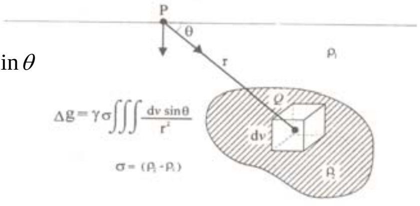


그림 2-1. 지하에 부존하는 초과질량에 의한 중력이상의 계산.

중력이상체의 질량계산

- 구에 의한 중력선속 계산

$$ds = 2\pi a \sin\theta d\theta$$

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

$$flux = \int \Delta g \bullet \mathbf{ds} = \int \Delta g \cdot ds = \int \frac{Gm}{a^2} 2\pi a^2 \sin\theta d\theta = 4\pi Gm$$

중력이상체의 질량계산

- 중력 이상체의 질량 계산

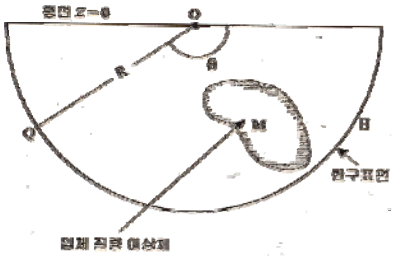


그림 2-2. 초과 중력 계산.

$m =$ 이상체가 포함된 경우 - 이상체가 포함되지않은 경우

$$= \rho_1 v_1 + \rho_2 v_2 - \rho_1 v_1 - \rho_1 v_2 = (\rho_2 - \rho_1) v_2$$

$$m = \frac{1}{2\pi G} \int \Delta g ds$$

$$M_A = \rho_2 v_2 = \frac{\rho_2 m}{\rho_2 - \rho_1}$$

중력측정

- 중력탐사에서 이상체에 의한 중력값 측정:0.01mgal
- 이상체에 의한 변화량을 절대중력의 범위에서 측정하기 어려움 → 절대중력측정 및 상대중력측정
- 절대중력측정
  - Falling body

$$S = \frac{1}{2} gt^2 \ (s = \text{falling distance} \quad t = \text{time})$$

$$g = \frac{2S}{t^2}$$

$$(1) : (g = \frac{2S_1}{t_1^2}) \times t_1 \rightarrow t_1 g = \frac{2S_1}{t_1}$$

$$(2) : (g = \frac{2S_1}{t_2^2}) \times t_2 \rightarrow t_{2g} = \frac{2S_2}{t_2}$$

$$(1) - (2) :$$

$$(t_1 - t_2) g = \frac{2S_1}{t_1} - \frac{2S_2}{t_2}$$

$$g = \frac{1}{t_1 - t_2} (\frac{2S_1 t_2 - 2S_2 t_1}{t_1 t_2})$$

  - Pendulum

The period $T = 2\pi\sqrt{\frac{l}{g}}$ l should be weightles s

physical pendulum

$$T = 2\pi\sqrt{\frac{I_c}{mgh}}$$

- 상대중력측정(숙제)

야외 조사

- 육상, 해상, 항공탐사 가능
- 중력에 영향을 주는 요인: 지형, 조석, 위도
  지하의 밀도
- 중력탐사에서 측정해야 하는 것들:
  고도, 위치, 중력값, 계기보정, 시간

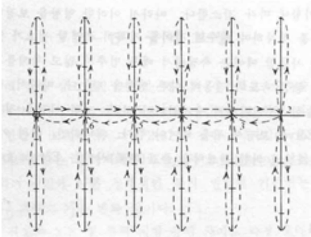


그림 2-36 중력 측정 경로의 예

야외 조사

- Station
  - 접근성이 용이해야 함.
  - 이상체의 크기와 깊이에 따라 측점간격 결정
  - 수십m에서 수 km
  - 특이한 지형변화가 있는 곳 피함
- 고도
  - 지형도, 고도계, 수준측량 등
  - 0.01 mgal의 중력차를 측정하려면, 고도차 5cm이내여야함
- 위치
  - GPS (Global positioning system)

중력보정 I (자료처리)

- 계기보정 (Drift correction)

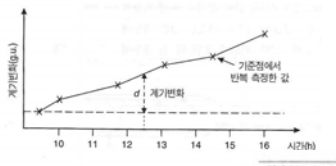


그림 2.14 계기변화 곡선(instrumental drift curve)

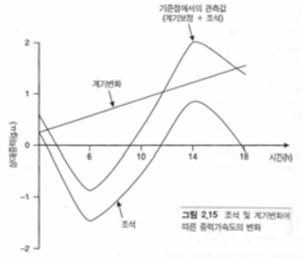
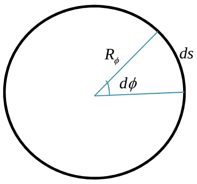


그림 2.15 조석 및 계기변화에 따른 중력가속도의 변화

- 조석보정(Tide correction)
  - 태양과 달에 의한 인력 또한 중력측정값에 영향을 미침
  - 육지에서의 조석 또한 위도와 시간에 따라 달라짐
  - 육지에서의 조석은 해양에서의 수분의 일에 해당

중력보정 2

- 위도보정 (latitude correction)



$$\frac{dg}{ds}: \text{difference btw north \& south}$$

$$\mathrm{g}_{theo} = g'_e(1+\alpha'\sin^2\phi+\beta'\sin^4\phi)$$

$$g_e = 978.03185 \quad \alpha = 0.00578895 \quad \beta = 0.00002346\ 2$$

$$\frac{\mathrm{dg}}{\mathrm{d}\phi} = 2g'_e\alpha'\sin\phi\cos\phi + 4\beta'\sin^3\phi\cos\phi$$

$$= g'_e\alpha'\sin 2\phi$$

$ds = R_\phi d\phi$이므로

$$\frac{dg}{ds} = \frac{1}{R_\phi}\cdot\frac{dg}{d\phi} = \frac{1}{R_\phi}\cdot g'_e\alpha'\sin 2\phi = 0.00812\sin 2\phi \text{ mgal/ 남북거리 10m}$$

중력보정 3

- 고도보정 (Elevation correction)
  - 프리-에어보정 (Free-air correction)

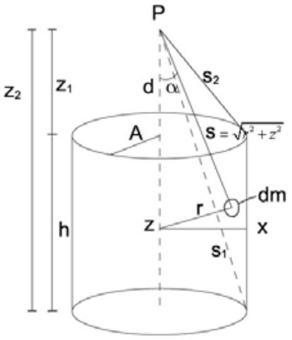
$$g_0 = \frac{Gm}{R^2} \quad g_1 = \frac{Gm}{(R+h)^2}$$

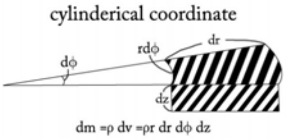
$$g_0 - g_1 = \frac{Gm}{R^2}(1-\frac{1}{(1+\frac{h}{R})^2} \approx \frac{Gm}{R^2}(1-(1-\frac{2h}{R}))$$

$$\frac{Gm}{R^2}\cdot\frac{2h}{R} = \frac{2g_0h}{R} = 0.3086hmgal$$

중력보정 4

- 고도보정 (Elevation correction)
  - 부게보정 (Bouguer correction)





중력보정4

$$dg_s = G\frac{dm}{S^2} = \frac{G\rho rd\phi drdz}{(r^2+z^2)},\ dg_z = dg_s \cdot \cos\alpha = G\frac{\rho rzd\phi drdz}{(r^2+z^{2)^{\frac{3}{2}}}}$$

$$g_z = \int_{z_1}^{z_2}\int_{r=0}^{A}\int_{\phi=0}^{2\pi} G\frac{\rho rd\phi drdz}{(r^2+z^2)^{\frac{3}{2}}} = 2\pi G\rho\int_{z_1}^{z_2}\int_{0}^{A}\frac{rzdrdz}{(r^2+z^2)^{\frac{3}{2}}}$$

$$= 2\pi G\rho\left[-\sqrt{A^2+{z_2}^2}+\sqrt{A^2+{z_1}^2}+(z_2-z_1)\right]$$

$$= 2\pi G\rho[-S_2+S_1+h]$$

when $z_2 \cong \infty$

$$-\sqrt{A^2+z^2} \rightarrow z_2$$

$$g_z = 2\pi G\rho\left[\sqrt{A^2+{z_2}^2}-z_1\right] = 2\pi G\rho[S_1-z_1]$$

when $A \cong \infty$

$$A^2+{z_1}^2 \approx A^2 \quad A^2+{z_2}^2 \approx A^2$$

$$\rightarrow g_z = 2\pi G\rho h$$

중력보정 4

- 고도보정 (Elevation correction)
  - 부게보정 (Bouguer correction)

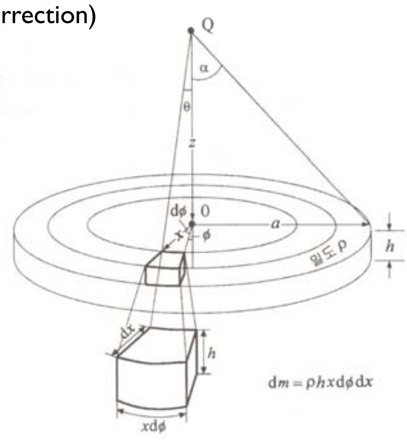


그림 2-3. 얇은 원판에 의한 중력가속도의 계산.

중력보정 5

- 지형보정 (Terrain correction)
  - 측점 주변에 산과 계곡 등 지형변화가 있을 때
- 지각평형보정
  - 큰 규모의 밀도 변화에 의한 효과를 보정하는 것
  - 광역탐사자료에 대해서만 보정함
- 에트뵈스보정 (Eötvös correction)
  - 해양 및 항공탐사에서만 수행

중력이상

- 프리에어 이상(Free-air anomaly)

$$\Delta g_{FAA} = \{g_{obs} \pm \Delta g_z + \Delta g_{FA}\} - g_{ref}$$

- 단순부게이상(Simple bouguer anomaly)

$$\Delta g_{SBA} = \Delta g_{FAA} - \Delta g_B = \{g_{obs} \pm \Delta g_L + \Delta g_{FA}\} - g_B - g_{ref}$$

- 부게이상(Bouguer anomaly)

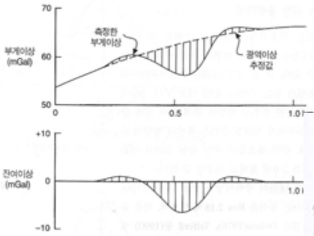
$$\Delta g_{SBA} = \Delta g_{SBA} + \Delta g_T$$

- 지각평형이상(Isostatic anomaly)

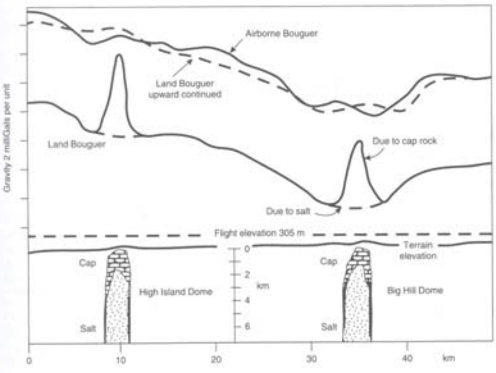
$$\Delta g_I = \Delta g_B \pm \Delta g_I$$

중력자료의 해석

- 광역이상과 잔여이상의 분리



- 상향연속과 하향연속



중력자료의 해석

- 2차수직미분

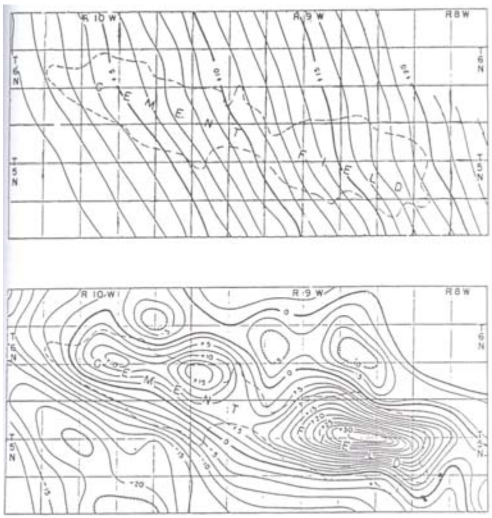


Figure 2.31 Observed Bouguer anomaly (contour interval 1 mGal) and second vertical derivative (contour interval 2.5 × 10^{-15} c.g.s.u.) maps over a Cement field in Oklahoma. From Elkins (1951), by permission

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중력자료의 해석

- 2차수직미분

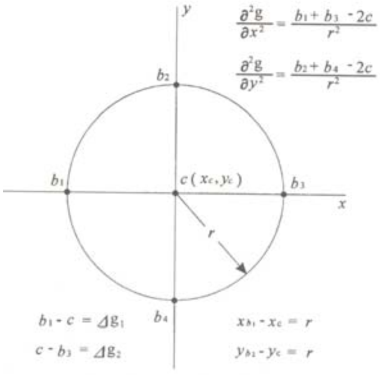


그림 2-9. 2차 수직미분을 구하기 위한 격자망.

x,y축의 미분값으로 z축의 변화를 알 수 있다.

Laplace equation 을 만족

$$\frac{d^2g}{dx^2} + \frac{d^2g}{dy^2} + \frac{d^2g}{dz^2} = 0$$

$$\frac{d^2g}{dx^2} = \frac{(\frac{b_2 - c}{r}) - (\frac{c - b_1}{r})}{r} = \frac{b_2 + b_1 - 2c}{r^2}$$

$$\frac{d^2g}{dy^2} = \frac{(\frac{b_4 - c}{r}) - (\frac{c - b_3}{r})}{r} = \frac{b_4 + b_3 - 2c}{r^2}$$

$$\frac{d^2g}{dz^2} = -(\frac{b_2 + b_1 + b_4 + b_3 - 4c}{r^2})$$

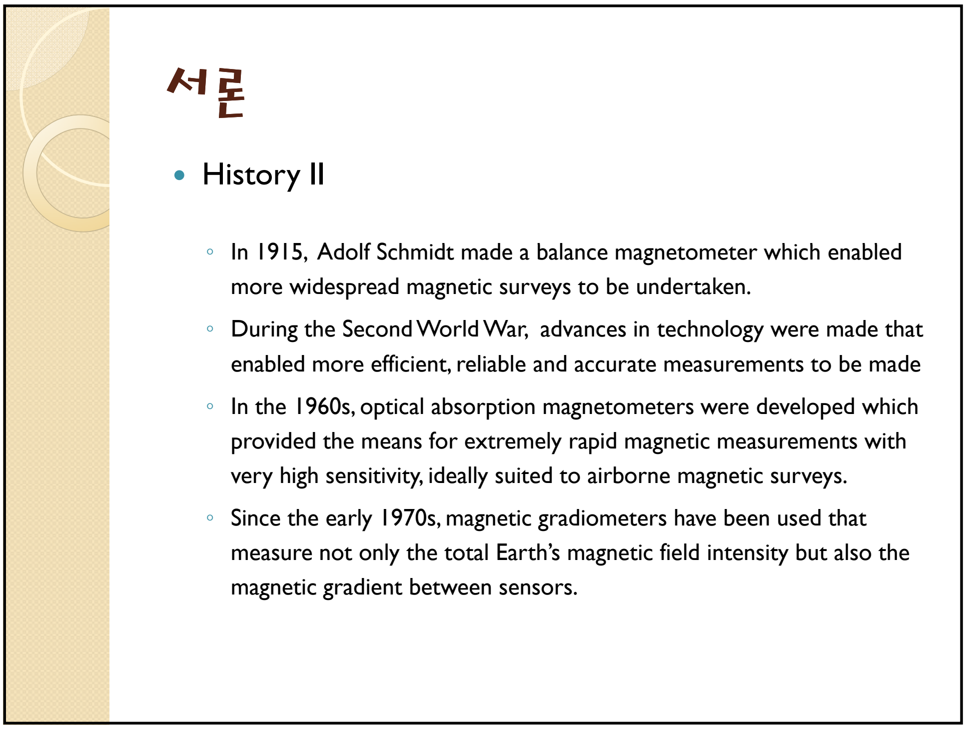
자력탐사

Magnetic method

자화강도를 측정함으로써 자기이상체를 탐지하거나 지하 구조를 추정하는 탐사

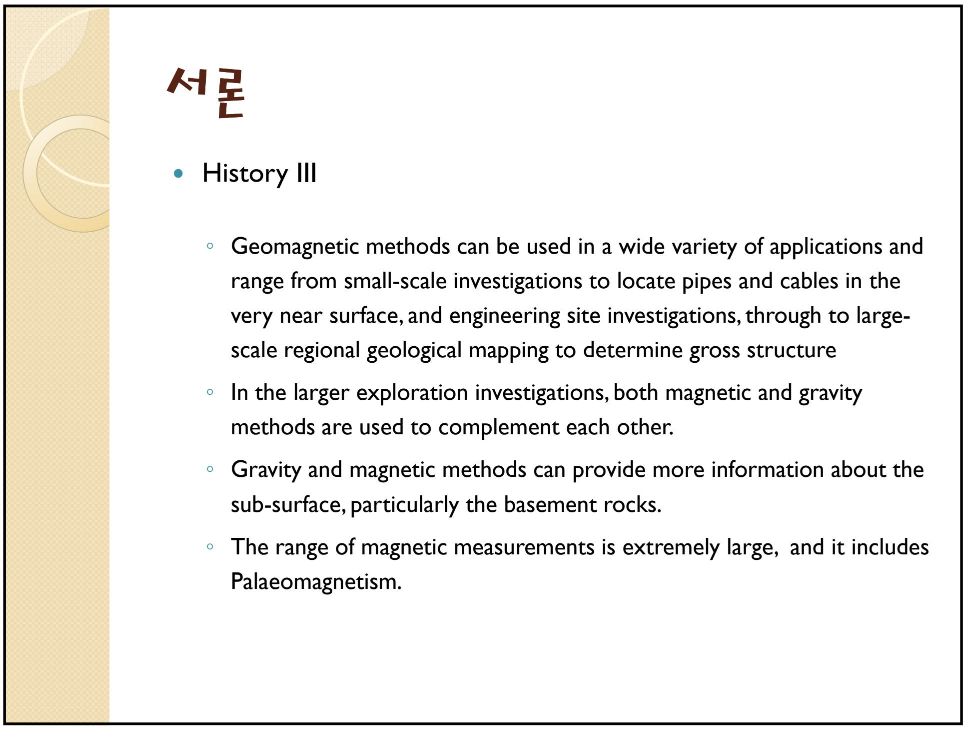
서론

- History I
  - 2nd century BC: Chinese first used *lodestone* (magnetite-rich rock) or *leading stone* in primitive direction-finding
  - 12th century: in Europe, reference was made to the use of a magnetic compass for navigation
  - In 1600, the first scientific analysis of the Earth's magnetic field and associated phenomena was published by the English physicist William Gibert in his book *De Magnete*
  - In 1640, measurements of variations in the Earth's magnetic field were made in Sweden to locate iron ore deposits
  - In 1870, Thalen and Tiberg developed instruments to measure various components of the Earth's magnetic field accurately and quickly for routine prospecting



서론

- History II
  - In 1915, Adolf Schmidt made a balance magnetometer which enabled more widespread magnetic surveys to be undertaken.
  - During the Second World War, advances in technology were made that enabled more efficient, reliable and accurate measurements to be made
  - In the 1960s, optical absorption magnetometers were developed which provided the means for extremely rapid magnetic measurements with very high sensitivity, ideally suited to airborne magnetic surveys.
  - Since the early 1970s, magnetic gradiometers have been used that measure not only the total Earth's magnetic field intensity but also the magnetic gradient between sensors.



서론

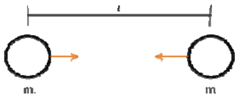
- History III
  - Geomagnetic methods can be used in a wide variety of applications and range from small-scale investigations to locate pipes and cables in the very near surface, and engineering site investigations, through to large-scale regional geological mapping to determine gross structure
  - In the larger exploration investigations, both magnetic and gravity methods are used to complement each other.
  - Gravity and magnetic methods can provide more information about the sub-surface, particularly the basement rocks.
  - The range of magnetic measurements is extremely large, and it includes Palaeomagnetism.

서론

- Application of geomagnetic surveys
  - Locating
    - Pipes, Cable, and Metallic objects
    - Buried military ordnance (Shell, Bombs, etc)
    - Buried metal drums of contaminated or toxic waste
    - Concealed mineshafts and adits (horizontal entrance to a mine)
  - Mapping
    - Archaeological remains
    - Concealed basic igneous dykes
    - Metalliferous mineral lodes
    - Geological boundaries between magnetically contrasting lithologies including faults
    - Large-scale geological structures

기초이론

- Magnetic force



$$\vec{F} = \frac{m_1 m_2}{\mu r^2} \vec{r_1}^{\,2} \text{ (in cgs system)}$$

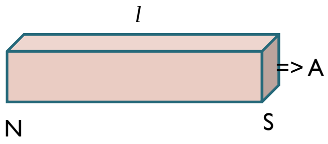
$$\vec{F} = \frac{m_1 m_2}{4\pi\mu r^2} \vec{r_1}^{\,2} \text{(in mks system)}$$

- Magnetic field

$$\vec{H} = \frac{m_1}{\mu r^2} \vec{r_1}^{\,2} \text{ (in cgs system)}$$

기초이론

- Intensity of magnetization and Magnetic moment



$$\overrightarrow{M} = lm\vec{r}_1$$ (음에서 양의 방향)

$$\vec{I} = \frac{\overrightarrow{M}}{V} = \frac{lm\vec{r}_1}{Al} = \frac{m\vec{r}_1}{A}$$

- Magnetic induction

$$B = \vec{H} + \vec{H}'$$
$$= \vec{H} + 4\pi\vec{I} = (1 + 4\pi k)\vec{H}$$
$$= \mu\vec{H} \quad \text{(in cgs system)}$$

$$\mathrm{B} = \mu_0(\vec{H} + \vec{I}) = \mu_0(1 + k)\vec{H} \quad \text{(in mks system)}$$

기초이론

- permeability

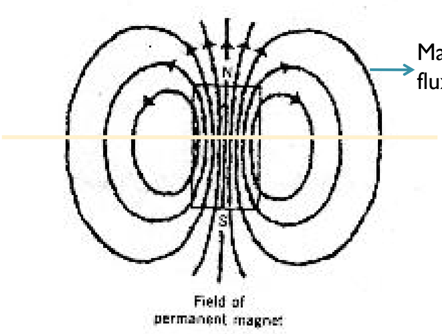
in vacuum

$$\mu_0 = 4\pi \times 10^{-7}\, wb/Am \quad \text{(in mks system)}$$

$$\mu_0 = 1\,\text{gauss / oersted} \quad \text{(in cgs system)}$$

기초이론

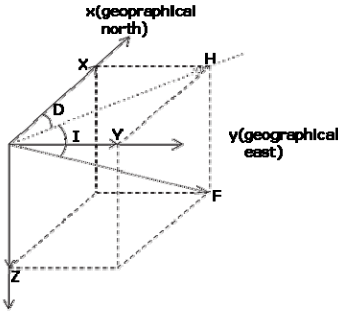
- Magnetic flux $\phi = B \bullet S$



Magnetic flux line

Magnetic equation plane

지구자기장



F : total magnetic field
H : horizontal magnetic field
Z : vertical magnetic field
I : inclination angle between the total field and horizontal compoonent
D : declinnation angle between horizontal component of the total field and geographic north

$$F^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2$$

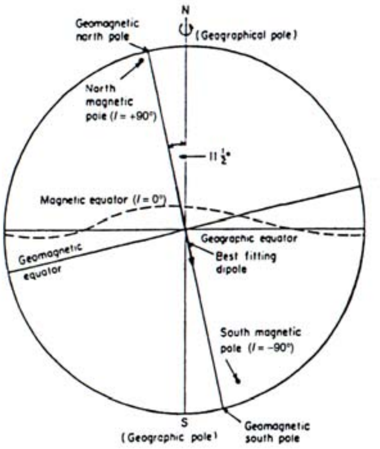
$$H = F\cos I \qquad Z = F\sin I$$

$$\tan I = \frac{Z}{H}$$

$$X = H\cos D \qquad Y = H\sin D$$

$$\tan D = \frac{Y}{X}$$

지구자기장

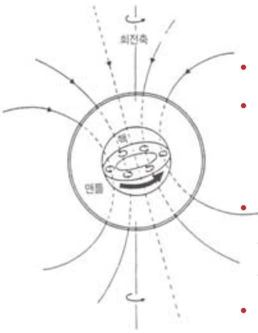


지구자기장의 기원

- 지구내부 또는 외부 기원일 수 있음
- 구형조화분석 결과: 99% from the interior and 1% from the source outside the earth
- 몇몇 가설
  - 지구자전때문에 형성됨→ Magnetization arising from the angular velocity of the earth is much too small.
  - 전하의 회전 → potential gradients in the earth would be impossibly large.
  - 영구자석설
    - too large for known surface rocks.
    - 지구내부에서의 고온(~2000˚C) : 모든 물질은 일정 온도보다 높아지면 자성을 잃음(Fe: 750˚C, Ni: 310˚C, Magnetite: 515˚C).
    - the Curie point

지구자기장의 기원

- 현재의 가설



  - 외핵 (1300 km to 3500 km)에서 유체의 회전에 의한 전류 형성 → 자기장 형성
  - 지구의 핵은 철과 니켈 등 전도체 물질로 이루어져 있음
  - 지구 내부의 물질이 전도체가 아니라고 하더라도 거대한 압력(~10^6 bars)이 전자를 방출하여 자유전자 가스를 형성할 수 있음
  - Self-excited dynamo: highly conductive fluid moves about in complex mechanical motion, while electric currents, possibly caused by chemical or thermal variations, flow through it.
  - 전류의 흐름이 자기장 유도
  - 다이나모가 쌍으로 존재할 경우 지구자기장의 약화 및 영년변화, 역전 등을 설명할 수 있음

지구자기장의 변화

- Secular variations 영년변화

-The geomagnetic field is far from permanent

-Inclination and Declination change as time goes by

-The intensity of the main magnetic field is decreasing at about 5% per century

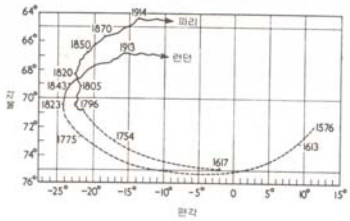


그림 3-13 수세기에 걸쳐 런던과 파리에서 측정한 지자기의 영년 변화 (Runcorn, 1962)

지구자기장의 변화

- 일변화

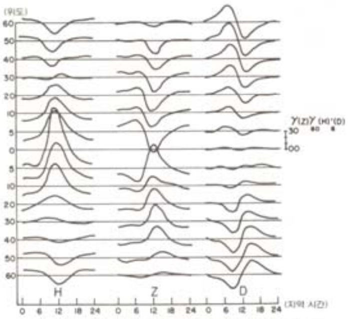


그림 3-11 위도에 따른 지자기장의 일변화 (Matsushita 외, 1967)
H : 수평성분, Z : 수직성분, D : 편각

- 자기폭풍

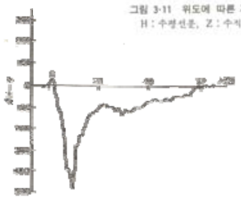


그림 3-12 [illegible]

암석의 대자율

<대자율>
염기성 화성암 > 산성 화성암> 변성암 > 퇴적암
<밀도>
변성암>화성암>퇴적암

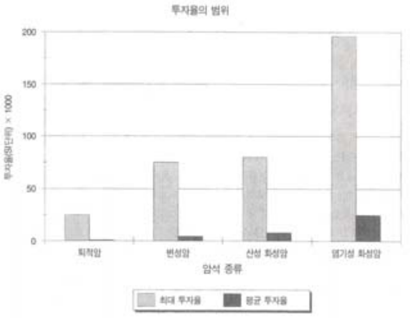


그림 3.7 주요 암석 종류에 따른 대자율

표 3.2 암석과 광물의 대자율(SI 단위)

광물 또는 암석 종류	대자율*
퇴적암	
백운암(순수)	−12.5 ~ +44
백운암(불순물)	20000
석회암	10 ~ 25000
사암	0 ~ 21000
셰일	60 ~ 18600
평균	**0 ~ 360**
변성암	
편암(schist)	315 ~ 3000
점판암(slate)	0 ~ 38000
편마암(gneiss)	125 ~ 25000
사문암(serpentenite)	3100 ~ 75000
평균	**0 ~ 73000**
화성암	
화강암	10 ~ 65
화강암(m)	20 ~ 50000
유문암(rhyolite)	250 ~ 37700
페그마타이트(pegmatite)	3000 ~ 75000
반려암(gabbro)	800 ~ 76000
현무암(basalt)	500 ~ 182000
해양 현무암	300 ~ 36000
감람암(peridotite)	95500 ~ 196000
산성(acid) 화성암 평균	**40 ~ 82000**
염기성(basic) 화성암 평균	**550 ~ 122000**
광물	
얼음(d)	−9
암염(d)	−10
석고(d)	−13
석영(d)	−15
흑연(d)	−80 ~ −200
황동광(chalcopyrite)	400
황철광(pyrite)(o)	50 ~ 5000
적철광(hematite)(o)	420 ~ 38000
자류철광(pyrrhotite)(o)	1250 ~ 6300000
티탄철광(ilmenite)(o)	314000 ~ 3800000
자철광(magnetite)(o)	70000 ~ 20000000

(d) = 반자성 물질, (o) = 광석, (m) = 자성 물질 포함
*k × 10^6 SI 단위. cgs 단위로 변환하려면 4π로 나누면 됨.

자력탐사

- 육상, 해상, 항공탐사 가능
- 일변화에 의한 효과를 제거하기 위해 일변화 측정

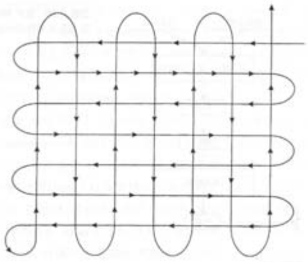


그림 3.25 선박 또는 항공기에 탑재된 자력계의 궤도. 때로는 모든 측선의 간격을 일정하게 하지 않고 측선간격의 10배마다 한 번씩 교차측선을 만들 수 있다.

자력보정

- Drift correction

  Instrument drift is generally not a major problem
- Diurnal variation correction

- IGRF correction (normal correction)

  (International geomagnetic reference field)

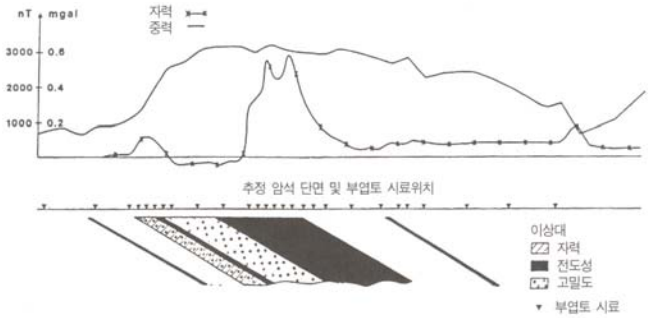
- Terrain correction

- RTP (reduction to the pole)

  Changes the actual indication to the vertical

자력탐사 자료 예

핀란드의 Saramaki광체의 지질단면도, 중력, 자력 자료

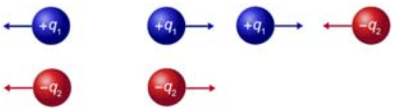


전기탐사

Electrical method

대지에 전류 전극을 꽂고 여기에 전류를 공급하여 전류가 흐르는 통로상의 암석이나 광물의 전기 전도도의 차이 기인한여 발생하는 지표에서의 전위분포를 전위전극에 의하여 측정하여 지하에 부존하는 전도체에 대한 정보를 탐지하는 것이다.

기초이론



- Coulomb's law

$$\vec{F} = k\frac{q_1 q_2}{r^2}\vec{r}$$

$$k(\text{electrostatic constant}) = \frac{1}{4\pi\varepsilon_0}\times 9\times 10^4\,\text{m/farad}$$

$$\varepsilon_0(\text{permitivity}) = 8.85\times 10^{-12}\,\text{farad/m}$$

$$1\text{farad} = 1C^2/n\cdot m$$

- Electric field intensity

$$\vec{E} = \frac{\vec{F}}{q_2} = k\frac{q_1}{r^2}\vec{r} = \frac{q_1}{4\pi\varepsilon_0 r^2}\vec{r}$$

기초이론

- The electric work
  - Work done by moving a point charge

$$W = \vec{F}\bullet\vec{s}$$

$$\vec{F}_a = -q\vec{E}$$

$$dW = \vec{F}_a\cdot d\vec{l} = -q\vec{E}\cdot d\vec{l}$$

q : positive

$d\vec{l}$: E 방향

기초이론

- Electric potential between two points

$$V_{AB}=\frac{W}{q}=-\int_{B}^{A}\vec{E}\cdot d\vec{l}=-\int_{rB}^{r_A}\vec{E}\cdot d\vec{r}=\frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r_A}-\frac{1}{r_B}\right)$$

- Electric potential due to a point charge

$$if\ \ r_B->\infty$$

$$V_{AB}=\frac{q}{4\pi\varepsilon_0 r_A}$$

기초이론

- Electric current

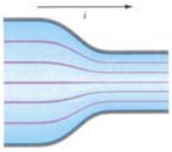
A stream of moving charges

$$i=\frac{dq}{dt} \qquad dq=idt$$

$$q=\int dq=\int idt$$

- Electric current density

$$\vec{J}=\frac{I}{d\vec{A}} \qquad I=\vec{J}\bullet d\vec{A}$$



- Resistance and Resistivity

$$R=\frac{\Delta V}{I} \qquad \rho=\frac{E}{J} \quad \text{(unit)}\frac{V/m}{A/m^2}=\Omega m$$

기초이론

- The relationship between resistance and resistivity

$$\rho = \frac{E}{J} = \frac{VA}{IL} = R\frac{A}{L}$$

- Conductivity

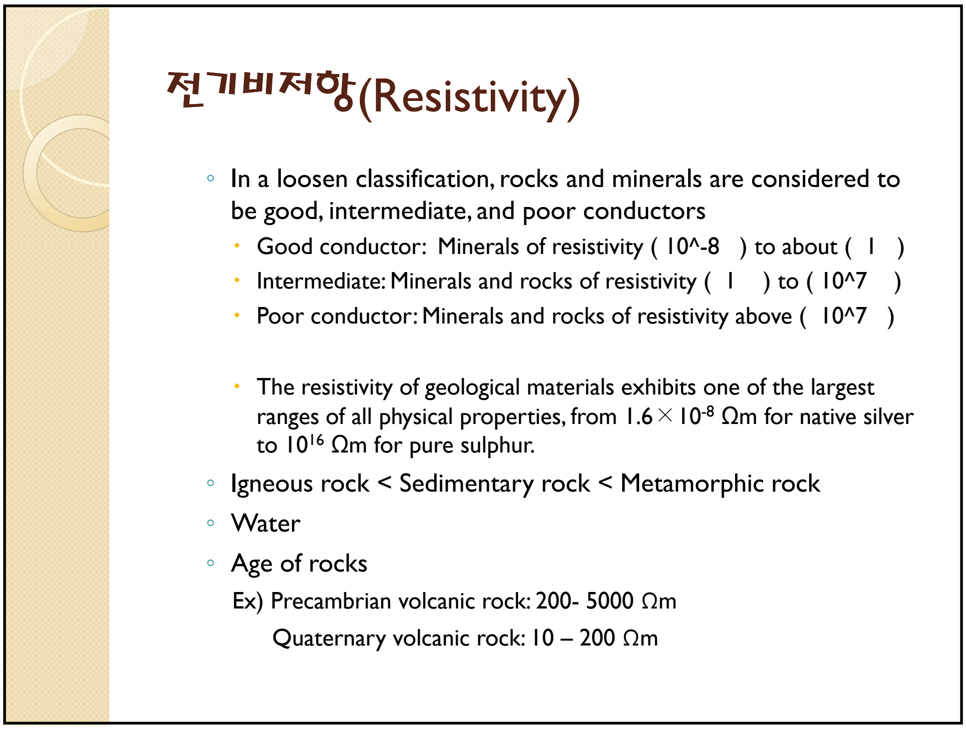
$$\sigma = \frac{1}{\rho} \ (\mathrm{unit}) \frac{1}{\Omega\mathrm{m}} = mho/m$$

- Ohm's law

$$\Delta V = IR$$

서론

- The objective of most modern electrical resistivity surveys is to obtain true resistivity models for the subsurface because they have geological meaning.
- Electrical prospecting involves the detection of surface effects produced by electric current flow in the ground
- An artificial source of current is introduced into the ground through point electrodes. Potential differences are measured at other electrodes in the vicinity of the current flow.
- Because we measure the currents as well as the potentials, it is possible to determine an apparent resistivity of the subsurface.
- Apparent resistivity

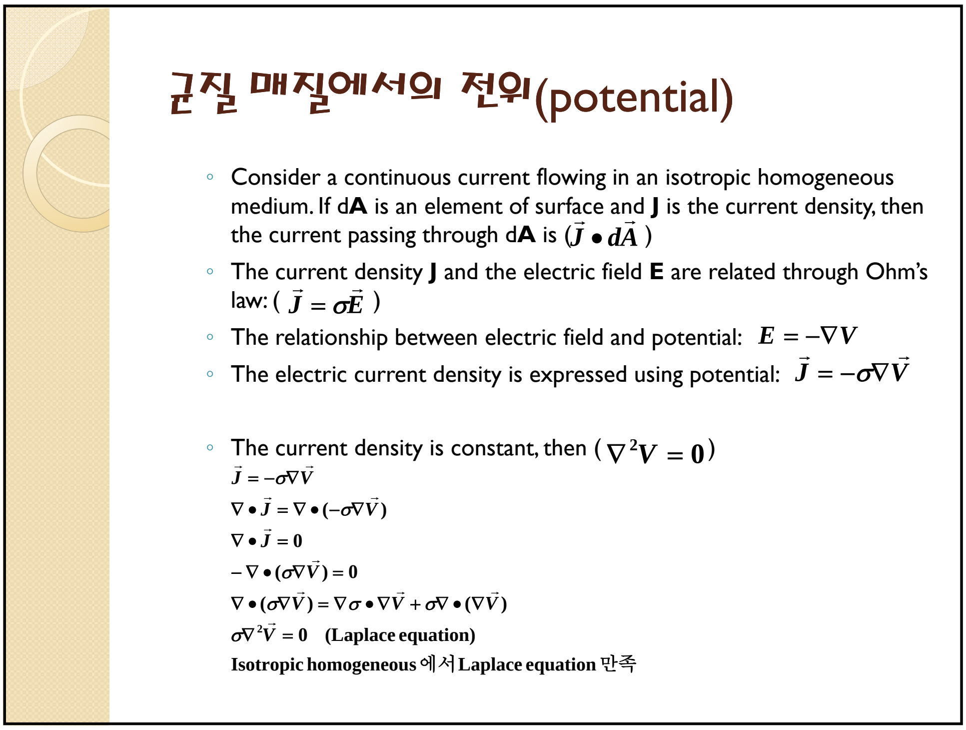


전기비저항(Resistivity)

- In a loosen classification, rocks and minerals are considered to be good, intermediate, and poor conductors
  - Good conductor: Minerals of resistivity (10^-8) to about (1)
  - Intermediate: Minerals and rocks of resistivity (1) to (10^7)
  - Poor conductor: Minerals and rocks of resistivity above (10^7)

  - The resistivity of geological materials exhibits one of the largest ranges of all physical properties, from 1.6×10^{-8} Ωm for native silver to 10^{16} Ωm for pure sulphur.
- Igneous rock < Sedimentary rock < Metamorphic rock
- Water
- Age of rocks

Ex) Precambrian volcanic rock: 200- 5000 Ωm
Quaternary volcanic rock: 10 – 200 Ωm



균질 매질에서의 전위(potential)

- Consider a continuous current flowing in an isotropic homogeneous medium. If d**A** is an element of surface and **J** is the current density, then the current passing through d**A** is ($\vec{J} \bullet d\vec{A}$)
- The current density **J** and the electric field **E** are related through Ohm's law: ($\vec{J} = \sigma\vec{E}$)
- The relationship between electric field and potential: $E = -\nabla V$
- The electric current density is expressed using potential: $\vec{J} = -\sigma\nabla\vec{V}$

- The current density is constant, then ($\nabla^2 V = 0$)

$$\vec{J} = -\sigma\nabla\vec{V}$$
$$\nabla \bullet \vec{J} = \nabla \bullet (-\sigma\nabla\vec{V})$$
$$\nabla \bullet \vec{J} = 0$$
$$-\nabla \bullet (\sigma\nabla\vec{V}) = 0$$
$$\nabla \bullet (\sigma\nabla\vec{V}) = \nabla\sigma \bullet \nabla\vec{V} + \sigma\nabla \bullet (\nabla\vec{V})$$
$$\sigma\nabla^2\vec{V} = 0 \quad \text{(Laplace equation)}$$

Isotropic homogeneous 에서 Laplace equation 만족

Single current electrode at depth

- An electrode is buried in a homogeneous isotropic medium. The current circuit is completed through another electrode, usually at surface, but in any case, the other electrode is located far away so that its influence is negligible.
- The current flows radially outward in all directions from the point electrode.
- In a spherical coordinate:

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=0 \qquad \nabla^2 V=\frac{d^2V}{dr^2}+\frac{2dV}{rdr}=0$$

$$r^2\frac{d^2V}{dr^2}+2r\frac{dV}{dr}=0 \qquad r^2\frac{dV}{dr}=A$$

$$V=-\frac{A}{r}+B \qquad \text{if r} \to \infty \ \ \text{V = 0 , } \therefore \text{B = 0}$$

$$V=-\frac{A}{r} \qquad I=J4\pi r^2 \ \ J=\sigma E$$

$$E=-\nabla V=-\frac{dV}{dr} \qquad I=-4\pi r^2\sigma\frac{A}{r^2}=-4\pi\sigma A$$

$$A=-\frac{I}{4\pi\sigma} \quad V=\frac{I\rho}{4\pi r}$$

실제탐사시, 반구를 측정하므로 $4\pi r^2 \Rightarrow 2\pi r^2$

$$\therefore V=\frac{I\rho}{2\pi r}$$

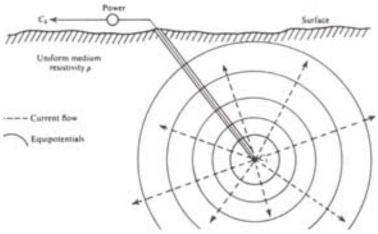


Figure 8.1. Buried point source of current in homogeneous ground.

Single current electrode at the surface

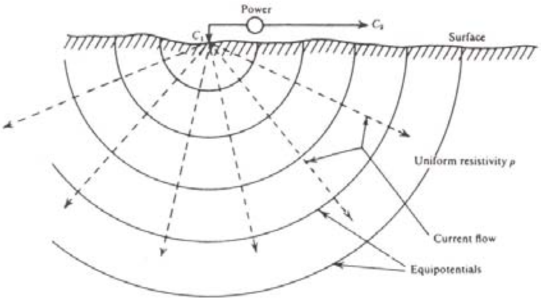


Figure 8.2. Point source of current at the surface of a homogeneous medium.

Two current poles at the surface

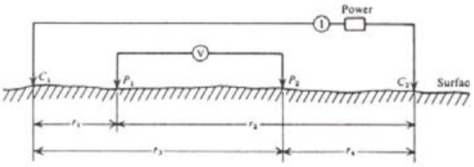


Figure 8.3. Two current and two potential electrodes on the surface of hom isotropic ground of resistivity ρ.

$$V = \frac{I\rho}{2\pi r}$$

$$V_{P_1} = \frac{I\rho}{2\pi r_1} + \frac{I\rho}{2\pi r_2}$$

$$V_{P_2} = \frac{I\rho}{2\pi r_3} - \frac{I\rho}{2\pi r_2}$$

$$\Delta V = V_{P_1} - V_{P_2} = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)$$

$$\rho_a = \frac{2\pi\Delta V}{I} \times \frac{1}{\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)} = \frac{2\pi\Delta V}{I} G$$

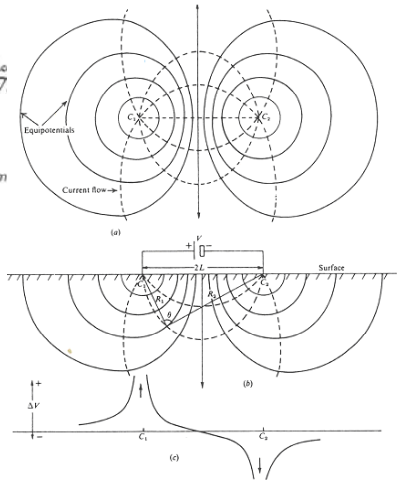
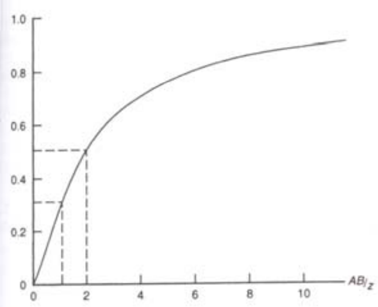


Figure 8.4. Equipotentials and current flow lines for two point sources of current on surface of homogeneous ground. (After Dobrin, 1960.) (a) Plan view. (b) Vertical section. (c) Potential variation at the surface along a straight line through the point sources.

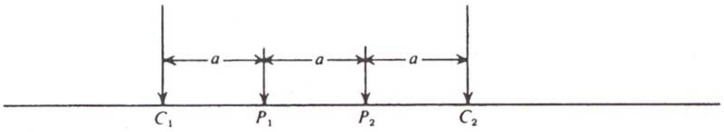
Electrode configuration

- The resistivity relationship has two parts:
- In reality, the subsurface ground is not homogeneous, and thus the resistivity obtained is no longer the 'true' resistivity. The resistivity that we obtain in fields is called apparent resistivity.
- The apparent resistivity is not a physical property of the subsurface media.



Proportion of current flowing
Below a depth z; AB is the current
Electrode separation

Wenner array



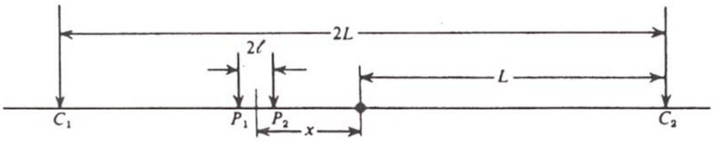
(a)

- Poles are uniformly spaced in a line
- Apparent resistivity:

$$\rho_a = \frac{2\pi\Delta V}{I} \times \frac{1}{(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4})}$$

$$= \frac{2\pi\Delta V}{I} \times \frac{1}{(\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a})} = \frac{2\pi\Delta Va}{I}$$

Schlumberger array



(b)

- The current electrodes are spaced much further apart than the potential electrodes
- Apparent resistivity: $r_1 = L - x - l >> 2l$

$$L - x >> 3l$$

$\therefore l^2$은 무시할수 있다.

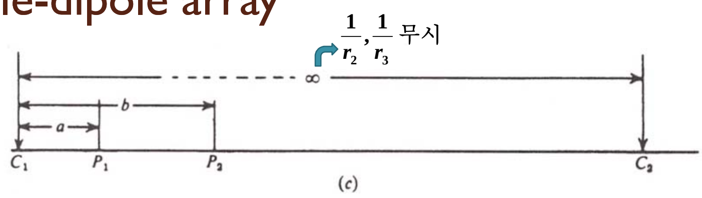
$$\rho_a = \frac{2\pi\Delta V}{I} \times \frac{1}{(\frac{1}{L-x-l} - \frac{1}{L+x+l} - \frac{1}{L-x+l} + \frac{1}{L+x-l})}$$

$$= \frac{\pi\Delta V}{2Il} \times \frac{(L^2 - x^2)^2}{L^2 + x^2}$$

if L >> x 라면

$$\frac{\pi\Delta V}{2Il} L^2 = \frac{\pi L^2}{I} \frac{\Delta V}{2l} = \frac{\pi a^2}{I} \frac{\Delta V}{\Delta a}$$

Pole-dipole array


$\frac{1}{r_2},\frac{1}{r_3}$ 무시

- One of the current electrodes is fixed at a great distance from the other three electrodes
- Apparent resistivity:

$$\rho_a = \frac{2\pi\Delta V}{I}\times\frac{1}{(\frac{1}{a}-\frac{1}{b})} = \frac{2\pi\Delta V}{I}\frac{ab}{b-a}$$

- When b=2a: $\frac{2\pi\Delta V}{I}\times 2a$

Pole-dipole array

- When the potential spacing is very small compared to the distance of potential electrodes from C_1

$$r_1 = a - \frac{\Delta a}{2}$$

$$r_3 = a + \frac{\Delta a}{2}$$

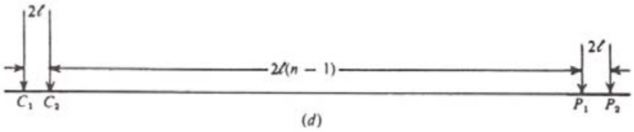
$$\rho_a = \frac{2\pi\Delta V}{I}\frac{a^2-(\frac{\Delta a}{2})^2}{\Delta a}$$

$$= \frac{2\pi a^2}{I}\frac{\Delta V}{\Delta a} = \frac{2\pi a^2}{I}\frac{\Delta V}{\Delta a} = \frac{2\pi a^2}{I}\frac{\partial V}{\partial a}$$

- When one of the potential poles is remote from the other potential pole:

$$\rho_a = \frac{2\pi\Delta V}{I}a$$

Dipole-dipole array



- The potential electrodes are closely spaced and remote from the current electrodes, which are also close together.
- Apparent resistivity

$$\rho_a = \frac{2\pi\Delta V}{I}\left(\frac{1}{\frac{1}{2ln} - \frac{1}{2l(n-1)} - \frac{1}{2l(n+1)} + \frac{1}{2ln}}\right)$$

$$= \frac{2\pi\Delta V}{I}\left(\frac{1}{\frac{1}{2l}\left(\frac{1}{n} - \frac{1}{n-1} - \frac{1}{n+1} + \frac{1}{n}\right)}\right)$$

$$= \frac{2\pi\Delta V}{I}\left(\frac{1}{\frac{1}{2l}\left(\frac{-2}{n(n-1)(n+1)}\right)}\right) = \frac{2\pi\Delta V}{I}(-ln(n-1)(n+1))$$

전기탐사 자료해석

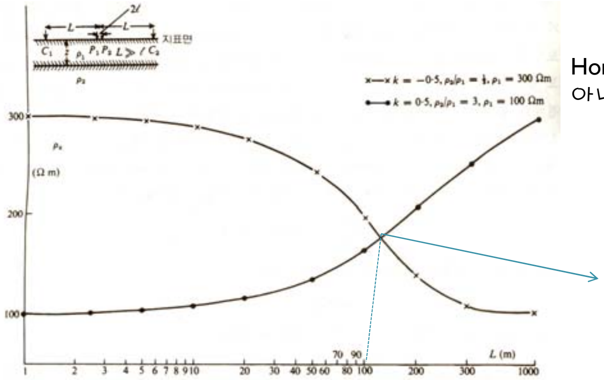


그림 4·36 슐럼버저 배열에 의한 수직탐사－수평 2층구조에 대한 ρ_a과 L의 그래프 (전기 비저항곡선은 z－100m로 하고, 식 (4.65b)으로부터 계산하였음)

Homogeneous 가 아니고 2층구조

Depth = 100

전기탐사 자료해석

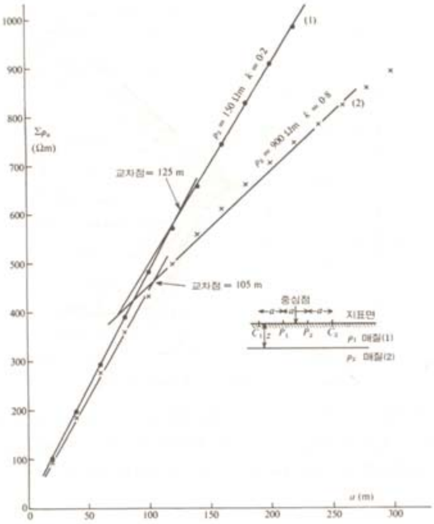


그림 4-37 웬너배열에서 ρ_a의 누적그래프

$\rho_1 = 100$ Ωm, $z = 100$ m, (1) $\rho_1/\rho_2 = 0.67$, $k = 0.2$; (2) $\rho_1/\rho_2 = 0.11$, $k = 0.8$

누적된 값

전기탐사 자료해석

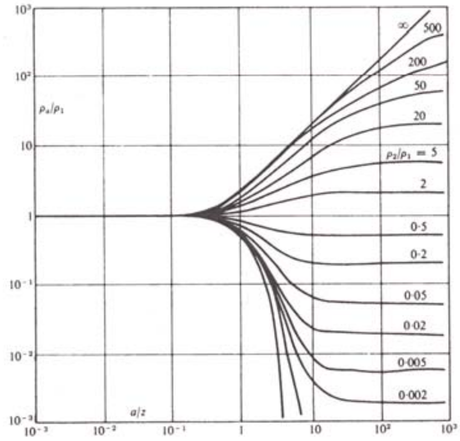
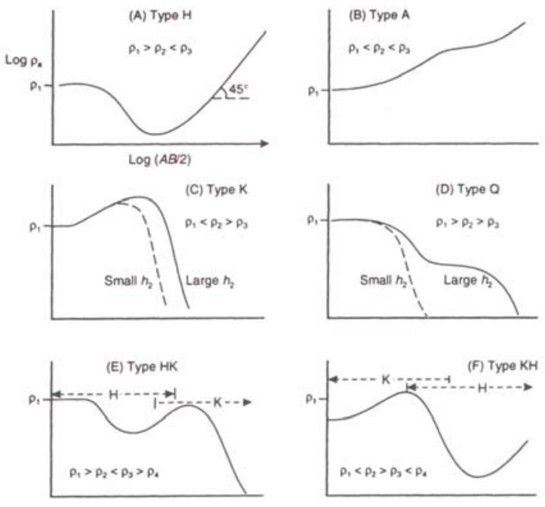


Figure 8.21. Wenner spread – master curves for two horizontal beds. (From Keller and Frischknecht, 1966.)

Field 자료와 비교해봐서, (1,1)에 맞는 field 자료의 수치를 보면 depth와 ρ측정가능하다

전기탐사 자료해석



전기탐사 자료해석

오차계산->modeling->오차계산 ->…….

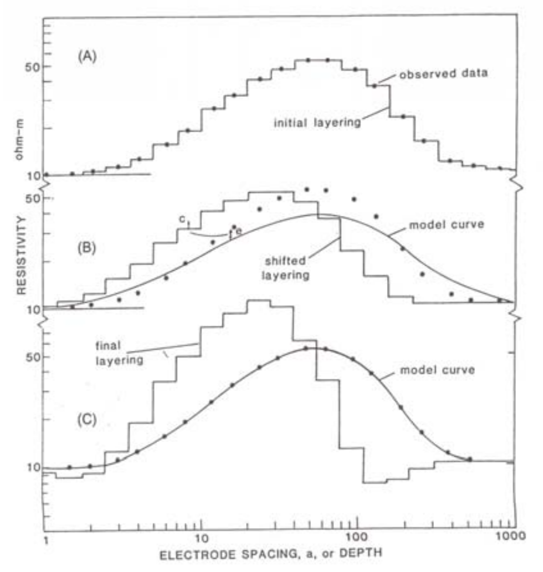
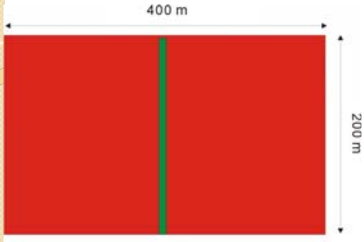


Figure 7.33 Automatic sounding inversion technique. (A) Observed data and initial layering. (B) Shifted layering and resulting model sounding curve. The difference (*e*) between the model and observed curves is used to apply a correction (c) to the layering. (C) The final layering and resulting model curve that is closely similar to the observed data. From Barker (1992), by permission

전기탐사 자료해석 (Modeling 자료 역산)

Pseudo section

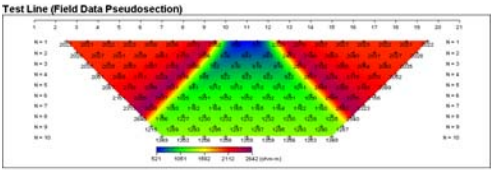


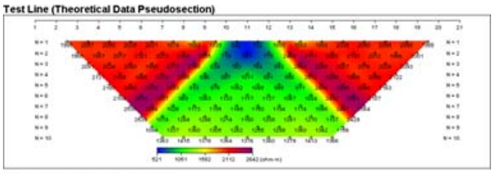
The width of the dyke is 1 m

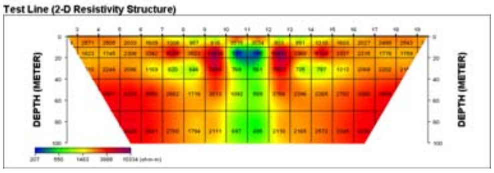
Electrode spacing is 20 m

Dipole-dipole method is used

The resistivities of dyke and the surrounding rock are 20 and 2000

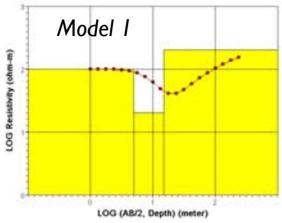

Test Line (Field Data Pseudosection)

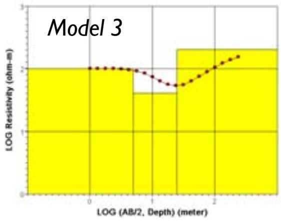

Test Line (Theoretical Data Pseudosection)


Test Line (2-D Resistivity Structure)

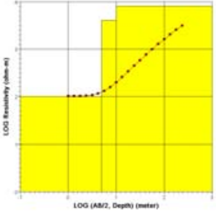
전기탐사 자료해석

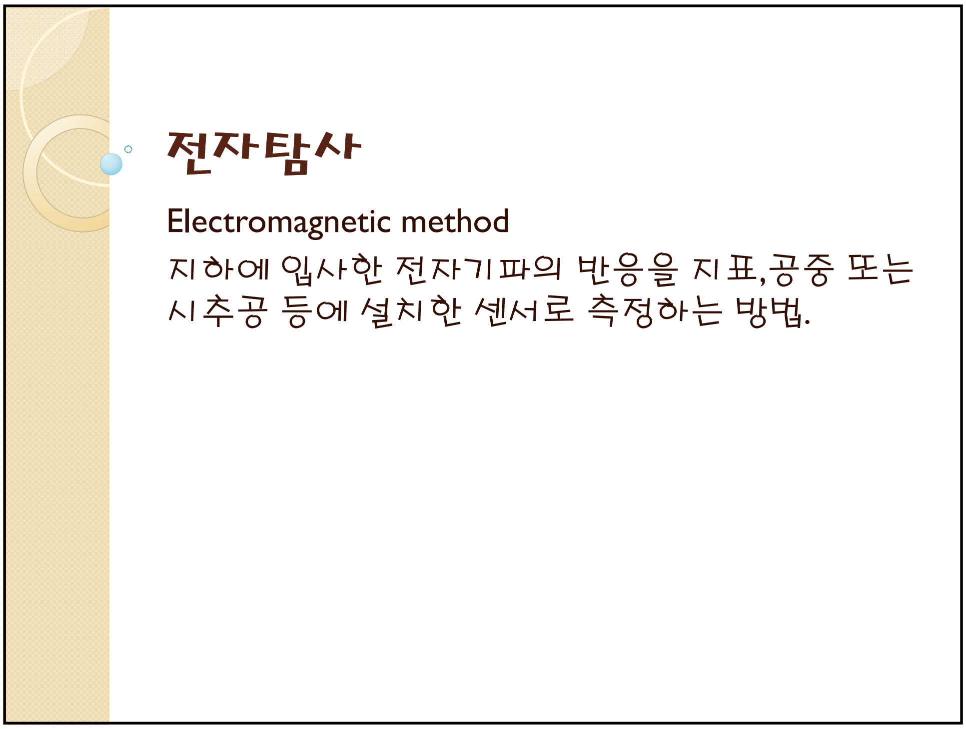
Layer	Model 1	Model 2	Model 3	Model 4
1	5 m / 100Ωm	5 m /100Ωm	5 m /100Ωm	5 m /100Ωm
2	10 m / 20Ωm	8 m/ 16Ωm	20 m/ 40 Ωm	10 m / 5 Ωm
3	200Ωm	200Ωm	200Ωm	200Ωm





3층구조(은폐성주의)

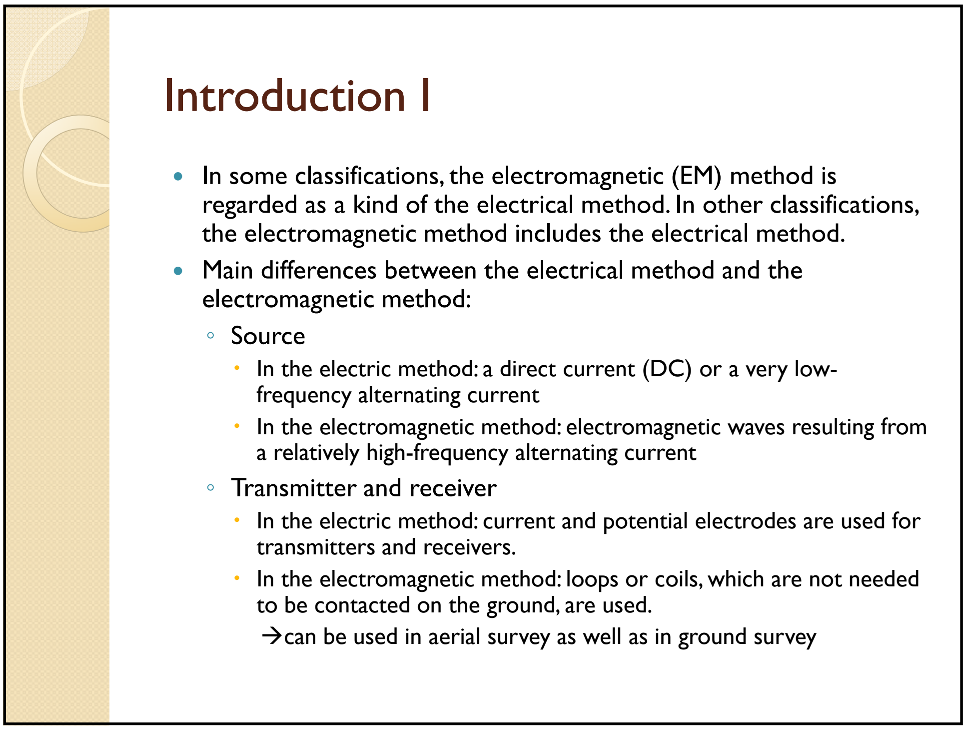




전자탐사

Electromagnetic method

지하에 입사한 전자기파의 반응을 지표,공중 또는 시추공 등에 설치한 센서로 측정하는 방법.



Introduction I

- In some classifications, the electromagnetic (EM) method is regarded as a kind of the electrical method. In other classifications, the electromagnetic method includes the electrical method.
- Main differences between the electrical method and the electromagnetic method:
  - Source
    - In the electric method: a direct current (DC) or a very low-frequency alternating current
    - In the electromagnetic method: electromagnetic waves resulting from a relatively high-frequency alternating current
  - Transmitter and receiver
    - In the electric method: current and potential electrodes are used for transmitters and receivers.
    - In the electromagnetic method: loops or coils, which are not needed to be contacted on the ground, are used.

      →can be used in aerial survey as well as in ground survey

Introduction II

- When currents are transmitted directly into the earth, the technique is called "a galvanic method". When currents are generated without the transmitter directly contacting the earth, the technique is called "an inductive method".
- Galvanic techniques depend upon good electrode contact and thus are not appropriate in areas that have high resistivity at the surface such as dry sand or glaciers. → EM method can be useful in such areas.
- The electric resistivity methods are (active), whereas most electromagnetic methods are (passive).
- In galvanic methods, depth penetration for a given resistivity structure is controlled only by the array geometry, in inductive techniques deeper penetration can also be obtained by using lower frequencies.

Introduction III

- Electromagnetic response can be induced by natural earth currents (MT: magnetotelluric method) or by artificial or controlled sources (EM in a narrow sense).
  - EM: most EM systems employ an active transmitter so that the source geometry and frequency can be controlled.
  - MT: the ambient electromagnetic radiation from ionospheric oscillations and from lightning discharges is utilized as a source for the telluric, magnetotelluric, and audio-frequency magnetic techniques.
    - Advantages of natural sources are the avoidance of the financial and logistical problems of a transmitter, and the availability of low frequency energy, which is expensive to generate artificially. However, sufficient signal strength is not always available, particularly in the 0.1 – 10 Hz frequency range.

Introduction IV

- EM methods are especially important, not only in mineral and hydrocarbon exploration, but increasingly in environmental geophysics applications. For hydrocarbon exploration, the EM methods have not been widely used.
- These days, however, marine MT begins to be used in oil exploration. The MT data can provide regional subsurface information, and thus can be used as a reconnaissance method.

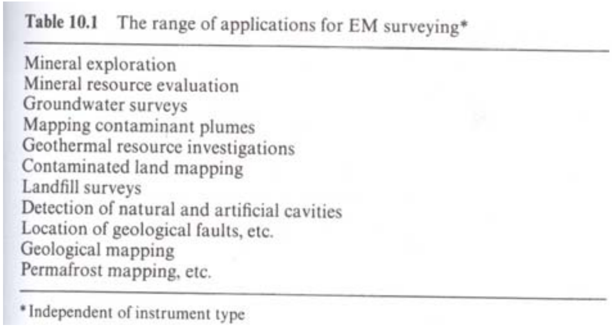


Table 10.1 The range of applications for EM surveying*

Mineral exploration
Mineral resource evaluation
Groundwater surveys
Mapping contaminant plumes
Geothermal resource investigations
Contaminated land mapping
Landfill surveys
Detection of natural and artificial cavities
Location of geological faults, etc.
Geological mapping
Permafrost mapping, etc.

*Independent of instrument type

Elementary Theory I

- Maxwell's equation
  - To understand the propagation and attenuation of electromagnetic waves, it is necessary to use Maxwell's equations in a form relating the electric and magnetic field vectors
  - E: electric field intensity (V/m), B: magnetic flux density (tesla T), J: current density (A/m^2), H: magnetic field intensity (A/m), D: the electric displacement (C/m^2)
  - Faraday's law: $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$

    자기장의 시간적 변화가 전기장을 유도할 수 있다.
    - An electric field exists in the region of a time-varying magnetic field, such that the induced emf (electromotive force) is proportional to the negative rate of change of magnetic flux.

Elementary Theory II

- Ampere's law : $\nabla \times \vec{H} = \vec{J} = \sigma\vec{E}$

  전기장의 변화에 의해서 자기장이 유도될 수 있다.
- Ampere-Maxwell law: $\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$
  - A magnetic field is generated in space by current flow and that the field is proportional to the total current (conduction plus displacement)
  - Maxwell introduced displacement current in Ampere's law.
  - The displacement current ($\partial \vec{D}/\partial t$) is a quantity that arises in a changing electric field and has the units of electric current. $\nabla \bullet (\varepsilon \vec{E}) = q_{enc}$
- Gauss' law for electric fields:
  - This integral (the net electric flux through the surface) is proportional to the net electric charge q_{enc} enclosed by the surface

Elementary Theory III

- Gauss' law for magnetic fields
  - There can be no net magnetic flux through the surface because there can be no net "magnetic charge" (individual magnetic poles) enclosed by the surface

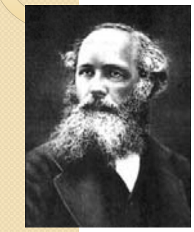
$$\nabla \bullet (\nabla \times \vec{E}) = -\nabla \bullet \left(\frac{\partial \vec{B}}{\partial t}\right) = -\frac{\partial}{\partial t}(\nabla \bullet \vec{B})$$

$$-\frac{\partial}{\partial t}(\nabla \bullet \vec{B}) = 0$$

$$\therefore \nabla \bullet \vec{B} = 0$$

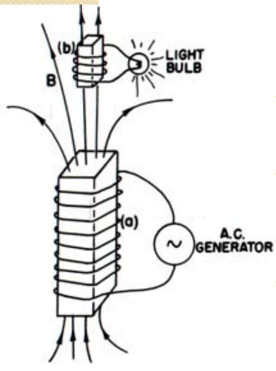
Elementary Theory IV

- Maxwell's achievements



  - Electricity and magnetism were originally thought to be unrelated.
  - In 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena
  - Electric field lines originate on positive charges and terminate on negative charges.
  - Magnetic field lines always form closed loop – they do not begin or end anywhere
  - A varying magnetic field induces an emf and hence an electric field (Faraday's law)
  - Magnetic field is also produced by changing electric field(Ampere's law)
  - Maxwell concluded that visible light and all other electromagnetic waves consists of fluctuating electric and magnetic fields, with each varying field inducing the other.

Elementary Theory IV



- An example (transformer)
  - Current flowing in conductive wire produces **H** field via Ampere's law assuming $\omega\varepsilon \ll \sigma$: $\nabla \times \vec{H} = \vec{I}$ **(Ampere's law)**
  - High μ value of core material enhances **B** field: $\vec{B} = \mu\vec{H}$
  - An E field is produced which curls around the magnetic field via Faraday's law: $\nabla \times \vec{E} = -iw\vec{B}\left(= -\frac{\partial \vec{B}}{\partial t}\right.$ **by Fourier transform)**
  - These processes result in voltage in the upper coil (Stoke's theorem): $\int (\nabla \times \vec{E}) \bullet \vec{n} ds = \oint \vec{E} \bullet d\vec{l} = V = IR$
  - From V=IR, current will flow in the upper coil, which lights bulb

Elementary Theory V

- Electromagnetic equations in an isotropic and homogeneous media

$\nabla \bullet \vec{E} = 0$ 증명

$$\nabla \bullet (\nabla \times \vec{H}) = \nabla \bullet \vec{J} + \nabla \bullet (\frac{\partial \vec{D}}{\partial t})$$

if no current source

$$\nabla \bullet \vec{J} = \nabla \bullet (\sigma \vec{E})$$

$$= \sigma(\nabla \bullet \vec{E}) + \vec{E} \bullet \nabla \sigma$$

$$\nabla \bullet \vec{J} = 0$$

$$\therefore \sigma(\nabla \bullet \vec{E}) = 0$$

$$\therefore \nabla \bullet \vec{E} = 0$$

Elementary Theory V

- Electromagnetic equations in an isotropic and homogeneous media

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad ....(1)$$

$$\nabla \times \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \quad ....(2)$$

$\nabla \times (1)$

$$\nabla \times \nabla \times \vec{E} = -\mu \frac{\partial}{\partial t}(\nabla \times \vec{H})$$

$$\nabla(\nabla \bullet \vec{E}) - \nabla^2 \vec{E} = -\mu \frac{\partial}{\partial t}(\sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t})$$

$\nabla \bullet \vec{E} = 0$이므로

$$\mu \frac{\partial}{\partial t}(\sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t}) - \nabla^2 \vec{E} = 0$$

$$\sigma\mu \frac{\partial \vec{E}}{\partial t} + \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = \nabla^2 \vec{E} \quad ....(\text{ㄱ})$$

$\nabla \times (2)$

$$\nabla \times \nabla \times \vec{H} = \sigma(\nabla \times \vec{E}) + \varepsilon \frac{\partial}{\partial t}(\nabla \times \vec{E})$$

$$\nabla(\nabla \bullet \vec{H}) - \nabla^2 \vec{H} = \sigma(\nabla \times \vec{E}) + \varepsilon \frac{\partial}{\partial t}(\nabla \times \vec{E})$$

$$\nabla(\nabla \bullet (\mu \vec{\mathrm{B}})) - \nabla^2 \vec{H} = \sigma(\nabla \times \vec{E}) + \varepsilon \frac{\partial}{\partial t}(\nabla \times \vec{E})$$

$\nabla \bullet \vec{B} = 0$ 이므로

$$-\nabla^2 \vec{H} = \sigma(-\mu \frac{\partial \vec{H}}{\partial t}) + \varepsilon \frac{\partial}{\partial t}(-\mu \frac{\partial \vec{H}}{\partial t})$$

$$= -\sigma\mu \frac{\partial \vec{H}}{\partial t} - \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2}$$

$$\therefore \nabla^2 \vec{H} = \sigma\mu \frac{\partial \vec{H}}{\partial t} + \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \quad ....(\text{ㄴ})$$

Elementary Theory V

- Electromagnetic equations in an isotropic and homogeneous media

  *** sinusoidal time variation**

  (ㄱ)에 $\vec{E} = E_0 e^{iwt}$ 대입

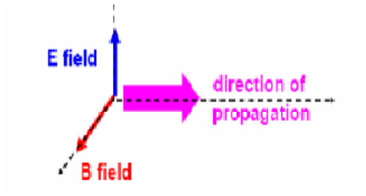
  $\nabla^2 \vec{E} = iw\mu\sigma\vec{E} - w^2\mu\varepsilon\vec{E}$

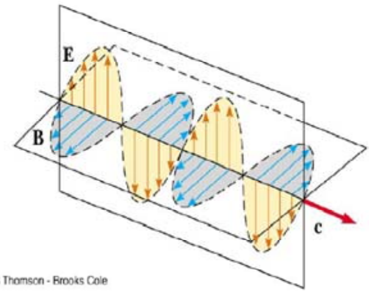
  (ㄴ)에 $\vec{H} = H_0 e^{iwt}$ 대입

  $\nabla^2 \vec{H} = iw\mu\sigma\vec{H} - w^2\mu\varepsilon\vec{H}$

Elementary Theory VI

- Features of electromagnetic waves
  - The electric and magnetic fields **E** and **B** are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a transverse wave
  - The electric field is always perpendicular to the magnetic field.
  - The cross product E × B always gives the direction in which the wave travels.
  - The fields always vary sinusoidally, just like the transverse waves
  - Electromagnetic waves travel at the speed of light in the free space: $C = \frac{1}{\sqrt{\mu_0\varepsilon_0}} = 2.99792\times10^8 m/s$
  - Light is an electromagnetic wave.





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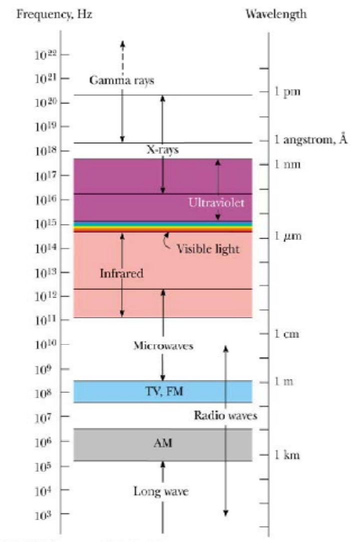

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Elementary Theory VII

- Attenuation of electromagnetic waves

$$\boxed{\nabla^2\mathbf{E} = i\omega\mu\sigma\mathbf{E} - \omega^2\mu\varepsilon\mathbf{E}} \qquad \boxed{\nabla^2\mathbf{H} = i\omega\mu\sigma\mathbf{H} - \omega^2\mu\varepsilon\mathbf{H}}$$

  - For a poor conductor ($\varepsilon=10\varepsilon_0$, $\mu=\mu_0$, and $\sigma=10^{-3}$ S/m poor conductor)

$$\varepsilon = 10\varepsilon_0 = 9\times10^{-11}\ \mathrm{F}/\mathrm{m} \qquad \mu = \mu_0 = 1.3\times10^{-6}\ \mathrm{H}/\mathrm{m}$$

$$\nabla^2 E = (i2.6\times10^{-5} - 4.6\times10^{-8})E \approx 0 \quad \textbf{(Laplace equation)}$$

  - For a good conductor ($\varepsilon=10\varepsilon_0$, $\mu=\mu_0$, and $\sigma=10^{3}$ S/m good conductor)

$$\nabla^2 E = (25i - 4.6\times10^{-8})E$$

$$= 25iE$$

$$\nabla^2 E = iw\mu\sigma E \qquad \textbf{(diffusion equation 만족)}$$

- Diffusion equation $\boxed{\nabla^2\mathbf{E} = i\omega\mu\sigma\mathbf{E} = \mu\sigma\frac{\partial\mathbf{E}}{\partial t}}$ $\boxed{\nabla^2\mathbf{H} = i\omega\mu\sigma\mathbf{H} = \mu\sigma\frac{\partial\mathbf{H}}{\partial t}}$
  - Assume that the wave is polarized in the xy plane and propagates along the z axis

$$E = E_x(z,t) = E_0 e^{iwt+mz}$$

$$H = H_y(z,t) = E_0 e^{iwt+mz}$$

$$\nabla^2 H = \frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = \frac{\partial^2 H}{\partial z^2} = H_0 m^2 e^{iwt+mz}$$

$$\mu\sigma\frac{\partial H}{\partial t} = i\mu\sigma wH_0 e^{iwt+mz}$$

$$\nabla^2 H = \mu\sigma\frac{\partial H}{\partial t}\ \text{여야 하므로}\qquad m^2 = i\mu\sigma w$$

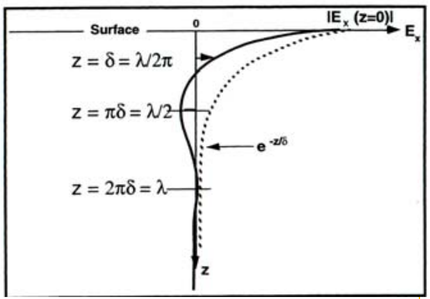
$$i = \frac{(1+i)^2}{2}\ \text{를 이용하면}\qquad m = \pm(1+i)\sqrt{\frac{\mu\sigma w}{2}} = (1+i)a$$

$$H = H_0 e^{iwt\pm(1+i)az}\ \text{인데}\quad z\rightarrow\infty\ \text{면}\ H\rightarrow 0\ \text{이므로}$$

$$H = H_0 e^{i(wt-az)}e^{-az}$$

Elementary Theory VIII

- Attenuation of electromagnetic waves
  - *cos(ωt-az)* indicates that waves are propagating as a sinusoid in the z direction.
  - e^{-az} indicates that waves *decay*, or *attenuate* in the z direction.
  - *Skin Depth* (δ) defined as the depth at which wave amplitude has decayed to 1/e its original value.

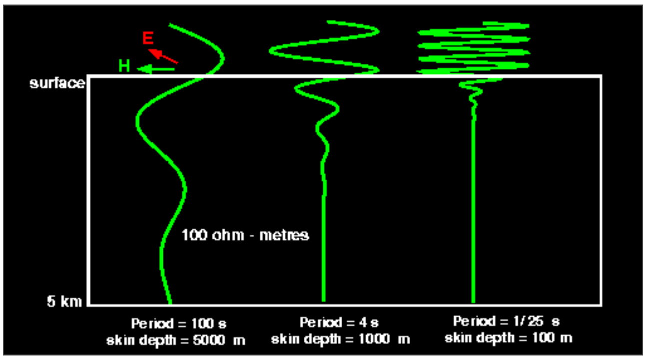


$$e^{-az} = \frac{1}{e}$$

$$az = 1 \qquad z = \frac{1}{a}$$

$$z = \sqrt{\frac{2}{\mu\sigma w}} = \sqrt{\frac{2\rho}{\mu w}} = \sqrt{\frac{\rho}{\pi\mu f}} = \sqrt{\frac{1}{\pi\mu}}\sqrt{\frac{\rho}{f}}$$

- Skin depth



Principles of EM survey

- Electromagnetic methods use the response of the ground to the propagation of incident alternating electromagnetic waves which are made up of two orthogonal vector components, an electric intensity (E) and a magnetic force (H) in a plane perpendicular to the direction of travel.
- For geophysical applications, frequencies of the primary alternating field are usually less than a few thousand hertz. The wavelength of the primary wave is of the order of 10-100 km while the typical source-receiver separation is much smaller (4 – 100 m). → The propagation of the primary wave and associated wave attenuation can be disregarded (Figure 10.8).

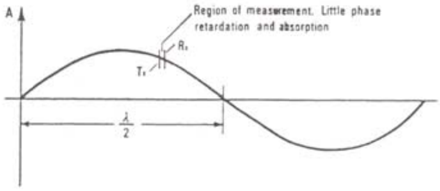


Figure 10.8 The physical separation of a transmitter (Tx) and receiver (Rx) is very small in relation to the wavelength of EM waves with frequencies greater than 3 kHz. Consequently, attenuation due to wave propagation can be ignored. Reproduced with permission from Beck (1991)

Principles of EM survey

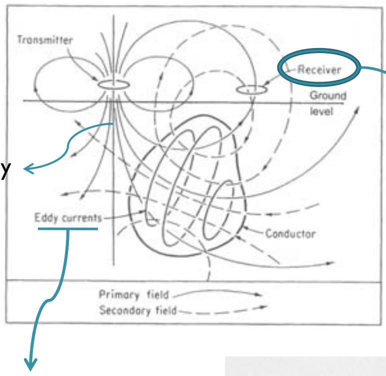
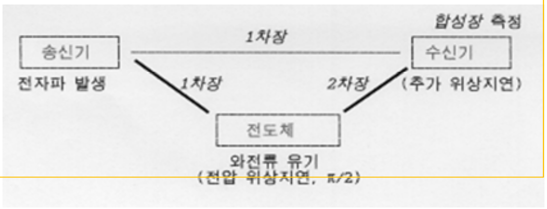


Figure 10.9 Generalized schematic of the EM surveying method. Reproduced with permission from Grant and West (1965)

Primary field + secondary field

Primary field

Primary field 에 의해 생긴 전기장 (와전류)



Principles of EM survey

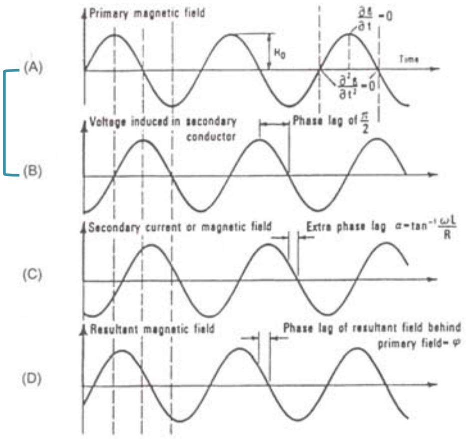


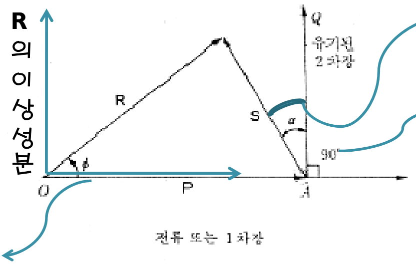
Figure 10.11 Relationships between induced voltages and associated phase lags between primary, secondary and resultant magnetic fields. Reproduced with permission from Beck (1981).

90 도 의 위상차

약간의 위상차
(전도체에 의해서)

(A)+(C)
Primary field +
Secondary field

Principles of EM survey



R의 이상성분

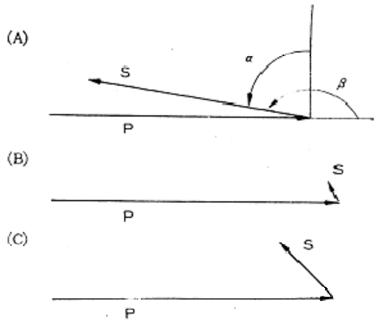
Conductor 에 의한 위상차
(전도도가 높을수록 커진다)

(A), (B)와의 위상차

R의 동상성분

P : Primary magnetic field
S : Secondary magnetic field
R : Resultant magnetic field

Principles of EM survey



<전도도>
A > B > C

길이 : field 의 세기를 나타냄

탄성파탐사

Seismic method

Introduction I

- Seismic method (exploration seismology) is widely used in petroleum exploration, civil engineering, groundwater searches
- Seismic method: high accuracy, high resolution, and great penetration.→ popular in petroleum exploration
- Exploration seismology is an offspring of earthquake seismology. When an earthquake occurs, the earth is fractured and the rocks move → Such a rupture generates seismic waves
- The objective of seismic exploration is to deduce information about the rocks, especially about the attitudes of the beds, from the observed arrival times and from variations in amplitude, frequency, phase, and wave shape.

- Reflection, Refraction, Surface wave methods

Introduction II

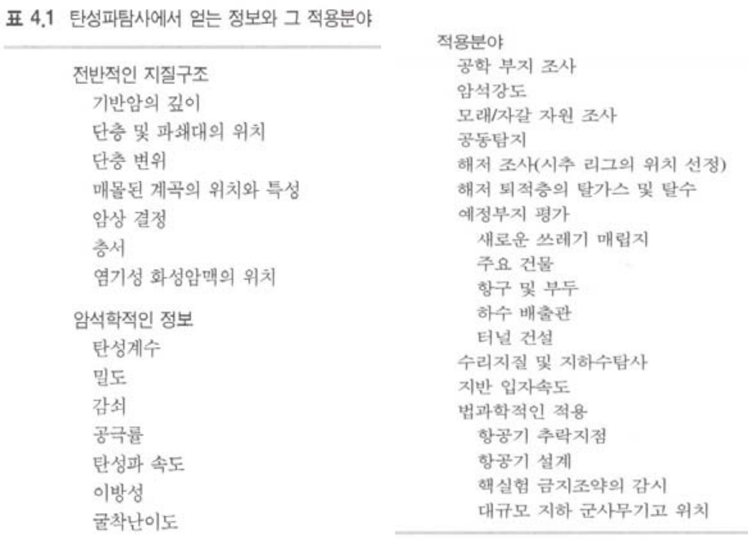


표 4.1 탄성파탐사에서 얻는 정보와 그 적용분야

- 전반적인 지질구조
  - 기반암의 깊이
  - 단층 및 파쇄대의 위치
  - 단층 변위
  - 매몰된 계곡의 위치와 특성
  - 암상 결정
  - 층서
  - 염기성 화성암맥의 위치
- 암석학적인 정보
  - 탄성계수
  - 밀도
  - 감쇠
  - 공극률
  - 탄성파 속도
  - 이방성
  - 굴착난이도

적용분야

- 공학 부지 조사
- 암석강도
- 모래/자갈 자원 조사
- 공동탐지
- 해저 조사(시추 리그의 위치 선정)
- 해저 퇴적층의 탈가스 및 탈수
- 예정부지 평가
  - 새로운 쓰레기 매립지
  - 주요 건물
  - 항구 및 부두
  - 하수 배출관
  - 터널 건설
- 수리지질 및 지하수탐사
- 지반 입자속도
- 법과학적인 적용
  - 항공기 추락지점
  - 항공기 설계
  - 핵실험 금지조약의 감시
  - 대규모 지하 군사무기고 위치

Basic Theory I

- Stress
  - The ratio of the force to area
  - Stress can be resolved into two components, one at right-angles to the surface (   ) and one in the plane of the surface (   ).
  - Stress at a point:
- Strain
  - The stressed body undergoes strain
  - The strain is the amount of deformation expressed as the ratio of the change in length (or volume) to the original length (or volume).

Basic Theory II

- Elasticity
  - The size and shape of a solid body can be changed by applying forces to the external surface of the body. These external forces are opposed by internal forces that resist the changes in size and shape
  - As a result, the body tends to return to its original condition when the external forces are removed.
  - The property of resisting changes in size and shape and of returning to the original condition when the external forces are removed

Basic Theory III

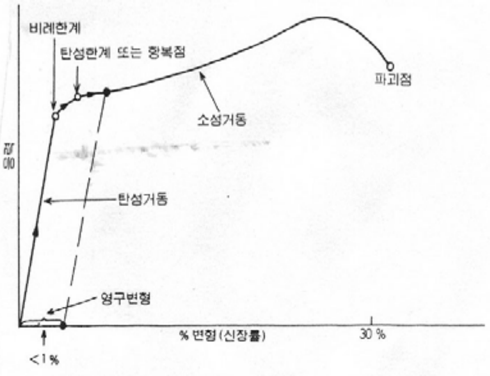
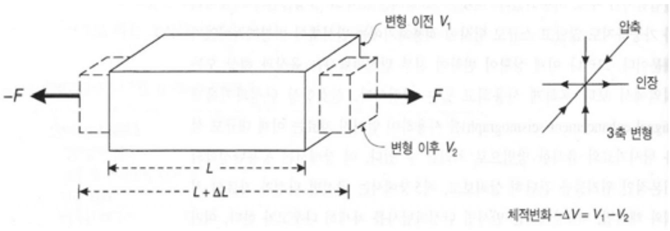


그림 6·1 고체의 응력－변형 관계

- Elasticity
  - Stress and strain are linearly dependent and the body behaves elastically until the yield point (elastic limit or proportional limit) is reached.
  - Below the yield point, on relaxation of stress, the body reverts to its pre-stressed shape and size.
  - At stresses beyond the yield point, the body behaves in a plastic or ductile manner and permanent damage results.
  - If further stress is applied, the body is strained until it fractures

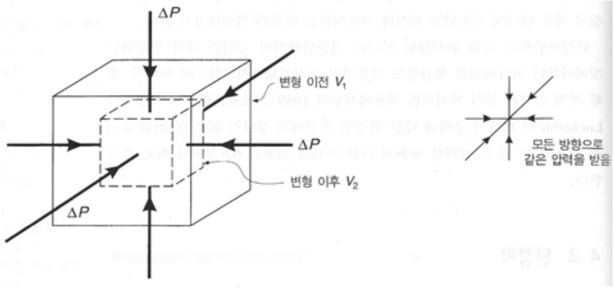
Basic Theory IV

- Elastic moduli
  - The relationship between stress and strain for any material is defined by various *elastic moduli.*
  - Young's modulus (영률) & Poisson's ratio (포아송의 비)



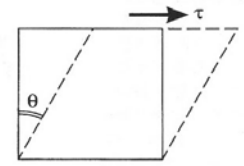
Basic Theory V

- Elastic moduli
  - Bulk modulus (체적탄성률)

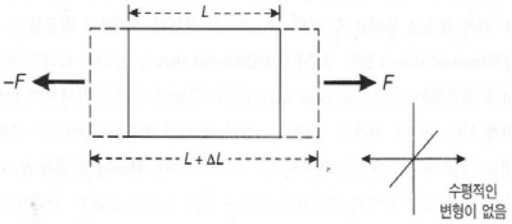


Basic Theory VI

- Elastic moduli
  - Shear (rigidity) modulus (a Lamé constant): 전단계수, 강성률



  - Axial modulus

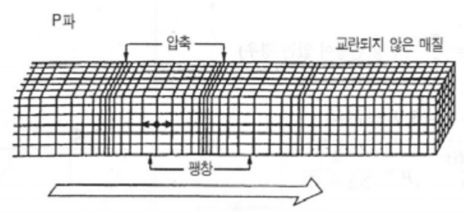


Seismic waves I

- Types of seismic waves
  - Seismic waves travel away from any seismic source at speeds determined by elastic moduli and the densities of the media through which they pass
  - There are two main types of seismic waves: body waves and surface waves
  - Body waves: waves that pass through the bulk of a medium are known as body waves
  - Surface waves: waves confined to the interfaces between media with contrasting elastic properties, particularly the ground surface, are called surface waves
  - Guided waves: are encountered in some applications, which are confined to particular thin bands sandwiched between layers with higher seismic velocities by total internal reflection.

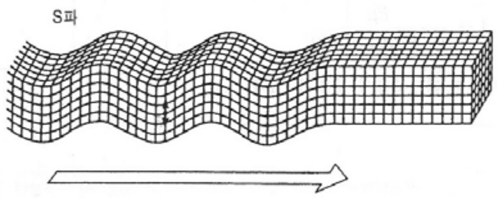
Seismic waves II

- Body waves
  - In unbounded homogeneous isotropic media, body waves only exist.
  - Two types of body waves can travel through an elastic medium.
  - P-wave
    - Material particles oscillate about fixed points in the direction of wave propagation by compressional and dilatational strain
    - Primary, longitudinal, dilatational, irrotational, or compressional waves (for example, sound waves)
    - Velocity



Seismic waves III

- Body waves
  - S-wave
    - Particle motion is at right-angles to the direction of wave propagation and occurs by pure shear strain
    - Secondary, transverse, rotational, or shear waves
    - When particle motion is confined to one plane only, the S-wave is said to plane-polarized (SH and SV waves)
    - Velocity

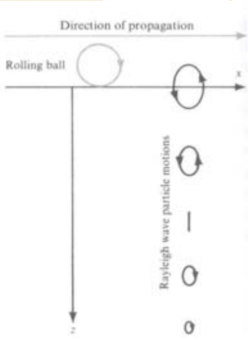


Seismic waves IV

- Surface waves
  - In an infinite homogeneous isotropic medium, only P and S wave exist. However, when the medium does not extend to infinity in all directions, other types of waves can be generated. They are called surface waves.
  - The waves do not penetrate deep into subsurface media. They are confined to the interfaces.
  - Large amplitude and low frequency waves
  - Rayleigh, Love, Stoneley waves

Seismic waves V

- Surface waves
  - Rayleigh waves
    - The combination of P and SV waves.
    - Travel along the free surface of the Earth with amplitudes that decrease exponentially with depth
    - Particle motion is in a retrograde elliptical sense in a vertical plane with respect to the surface



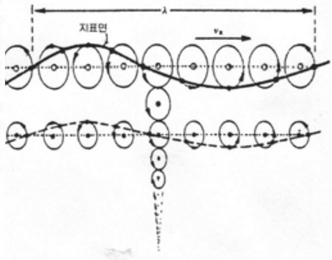
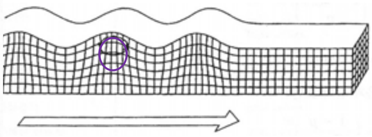


그림 6-13 레일리파와 입자의 운동

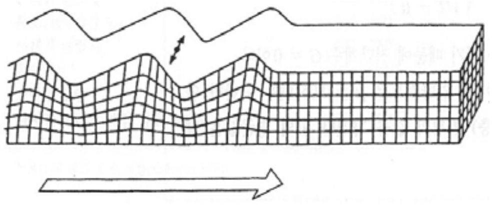


Seismic waves VI

- Surface waves
  - Rayleigh waves
    - Velocity depends upon the elastic constants near the surface and is always less than the S wave velocity β. When the Poisson's ratio is 0.25, the Rayleigh wave velocity is 0.92β
    - Because the elastic constants change with depth, the velocity of Rayleigh waves varies with wavelength. → A variation of velocity with wavelength (or frequency) is called dispersion.
    - Rayleigh waves are dispersive in layered media, whereas they are not dispersive in semi-infinite homogeneous media.
    - Groundroll which can mask reflections on a seismic record
    - Assessment of stability of structure such as dam and road (Spectral analysis of the surface waves: SASW). The SASW employs the dispersive features of Rayleigh waves.

Seismic waves VII

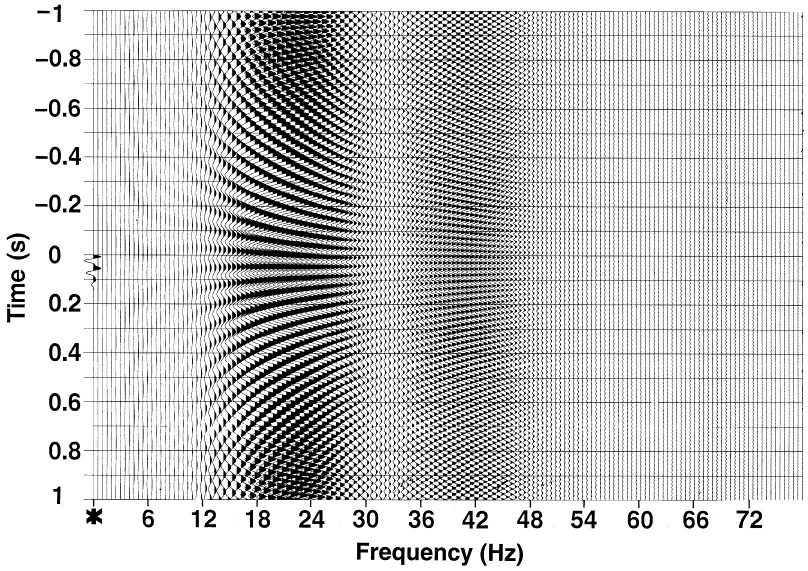
- Surface waves
  - Love waves
    - Love waves occur only where a medium with a low S-wave velocity overlies a half space with a higher S-wave velocity
    - Velocities are intermediate between the S-wave velocity at the surface and that in deeper layers.
    - Particle motion is at right-angles to the direction of wave propagation but parallel to the surface
    - These are polarized shear waves



Seismic waves VIII

- Surface waves
  - Stoneley waves
    - Similar to Rayleigh waves
    - Propagate along the interfaces between fluid and solid media
  - Surface waves have the characteristic that their waveform changes as they travel because different frequency components propagate at different rates, a phenomenon known as wave dispersion
  - The dispersion patterns are indicative of the velocity structure through which the waves travel, and thus surface waves generated by earthquakes can be used in the study of the lithosphere and asthenosphere

Seismic wave & Fourier series



Velocity & Density

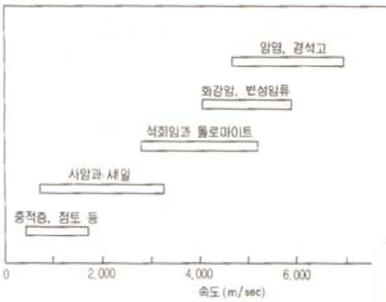


그림 6·28 각종 암석의 탄성파속도 분포

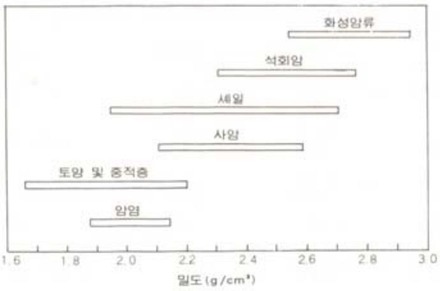
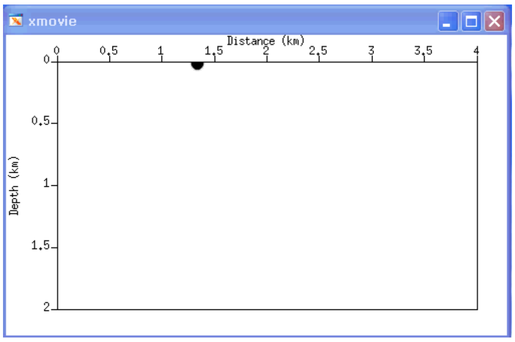
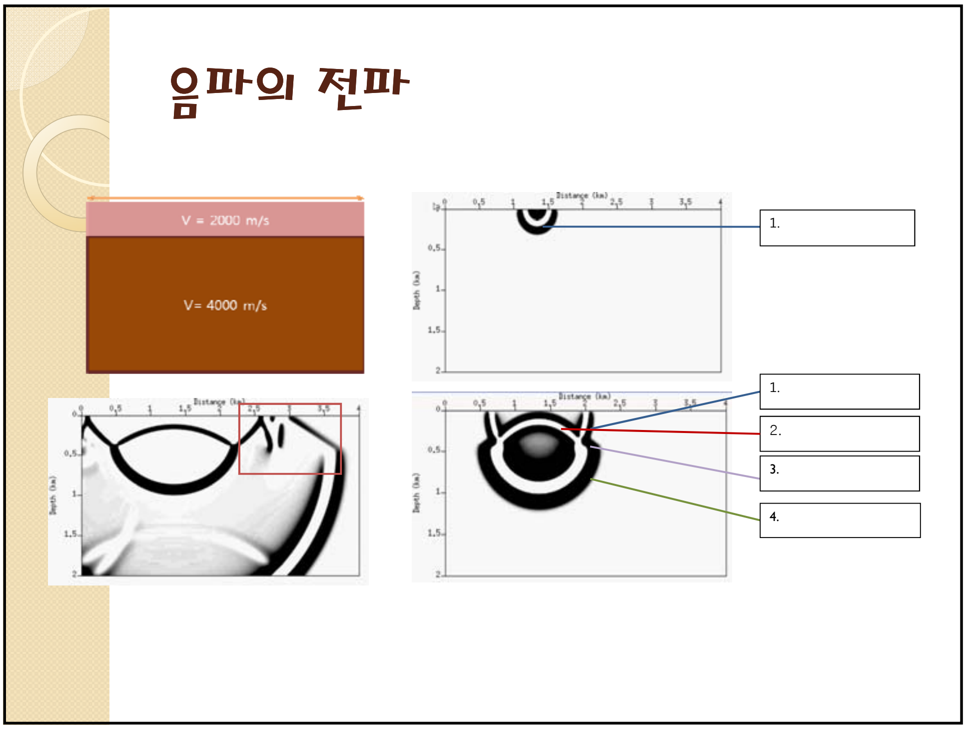


그림 6·27 각종 암석의 체적밀도 분포

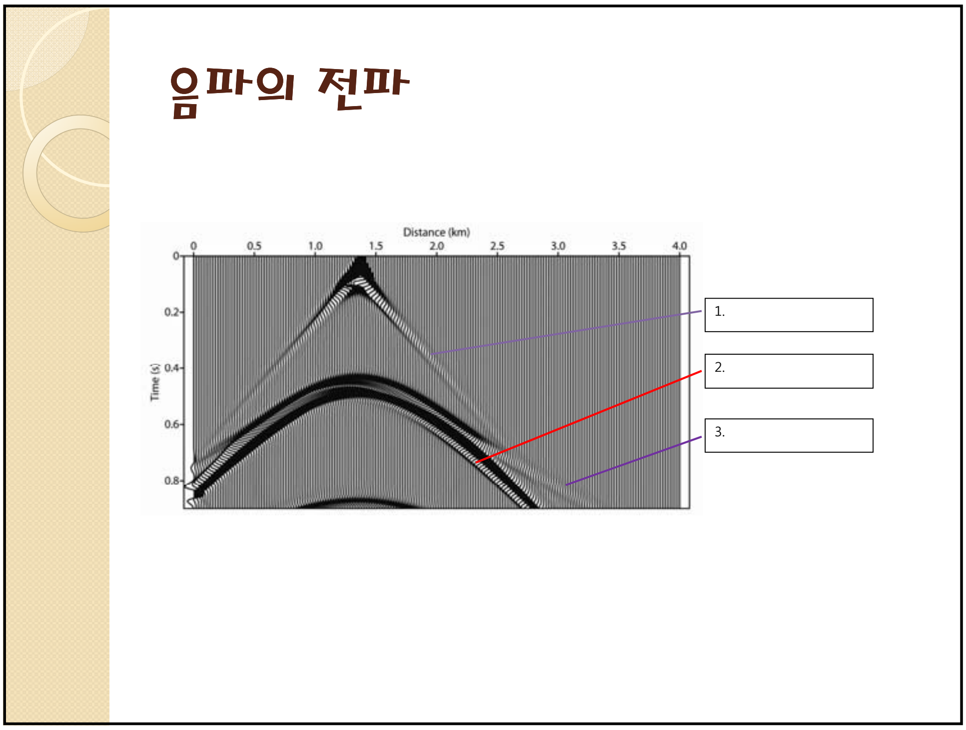
음파의 전파





음파의 전파

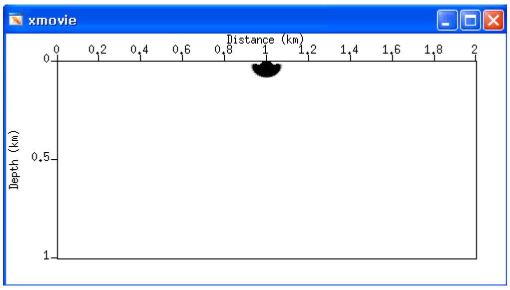
V = 2000 m/s
V= 4000 m/s
Distance (km)
Depth (km)
0
0.5
1
1.5
2
2.5
3
3.5
4
1.
1.
2.
3.
4.



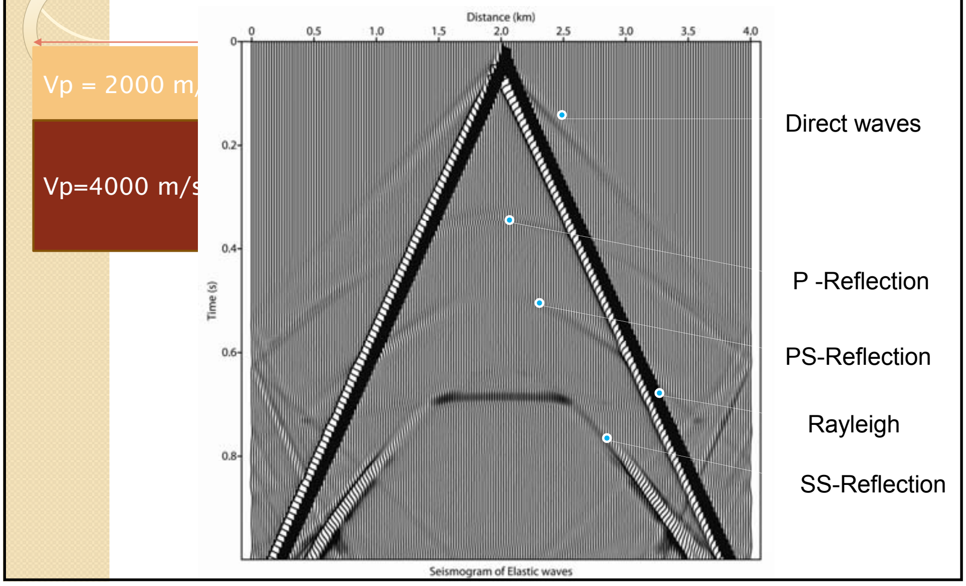
음파의 전파

Distance (km)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (s)
0.2
0.4
0.6
0.8
1.
2.
3.

탄성파의 전파



탄성파의 전파



Seismic exploration

- Refraction method
  - 선두파(임계굴절파 이용)
  - 비교적 천부구조에 대한 정보 제공
  - 지반조사 등에 활용
  - 반사법 탐사자료 해석시 보조자료로 이용
- Reflection method
  - 반사파
  - 심부구조에 대한 정보 제공
  - 석유, 가스, 메탄가스하이드레이트 탐사
  - 지반조사에도 활용
- Surface method
  - 표면파의 분산 특성 이용
  - 지반 조사 및 구조물의 안정성 평가에 활용

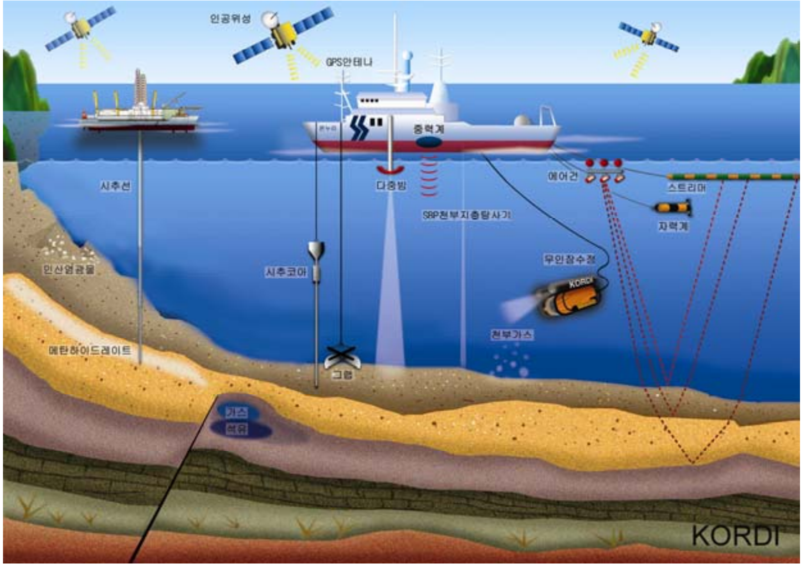
육상송신원


Source (Wacker Rammer)

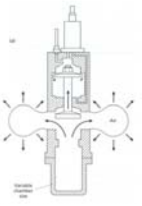
육상수진기

종류	원리	비고
지오폰	자석과 코일	10−100Hz, 3성분 측정가능
하이드로폰	압전 소자	P파만 측정 물이 필요

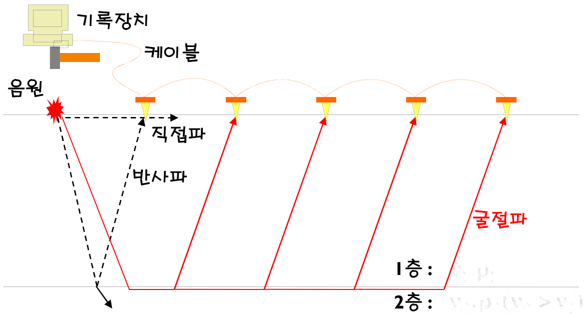
해양탄성파탐사 모식도



해상 송신원 및 수진기

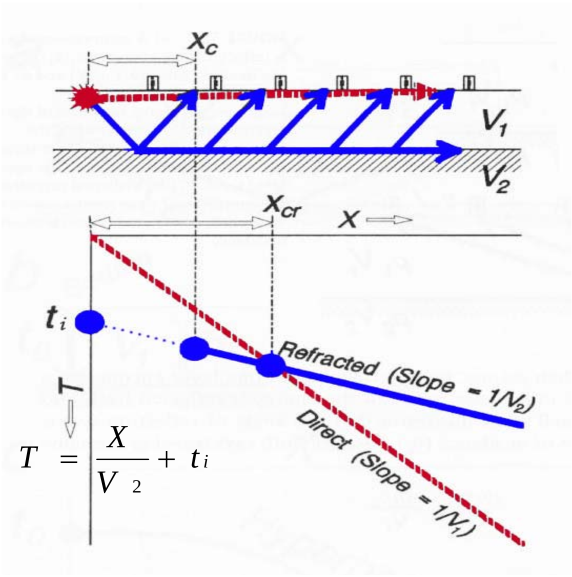


굴절법 탐사 모식도



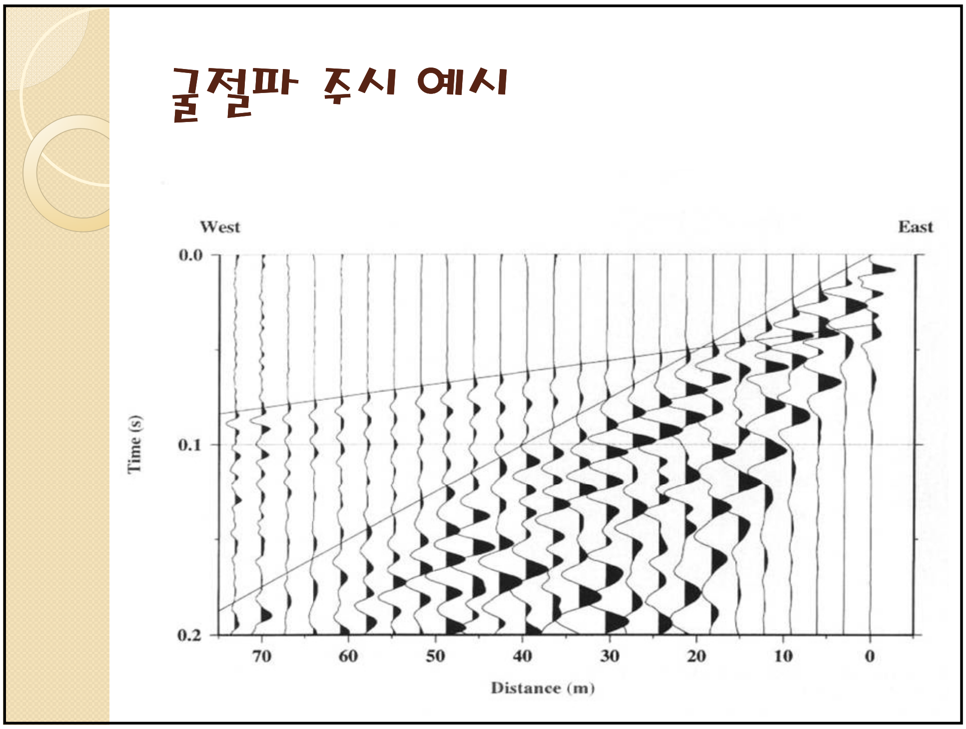
- ✓ 굴절법 탐사에서는 타겟 깊이의 3-5배 정도로 수진기를 벌려줘야 함
- ✓ 따라서 반사법 탐사에 비해 수진기 간격이 넓음
- ✓ 파가 먼거리를 전파해 가므로 반사법 탐사보다 저주파의 송신원 및 저주파 대역의 수진기 필요

수평층 구조

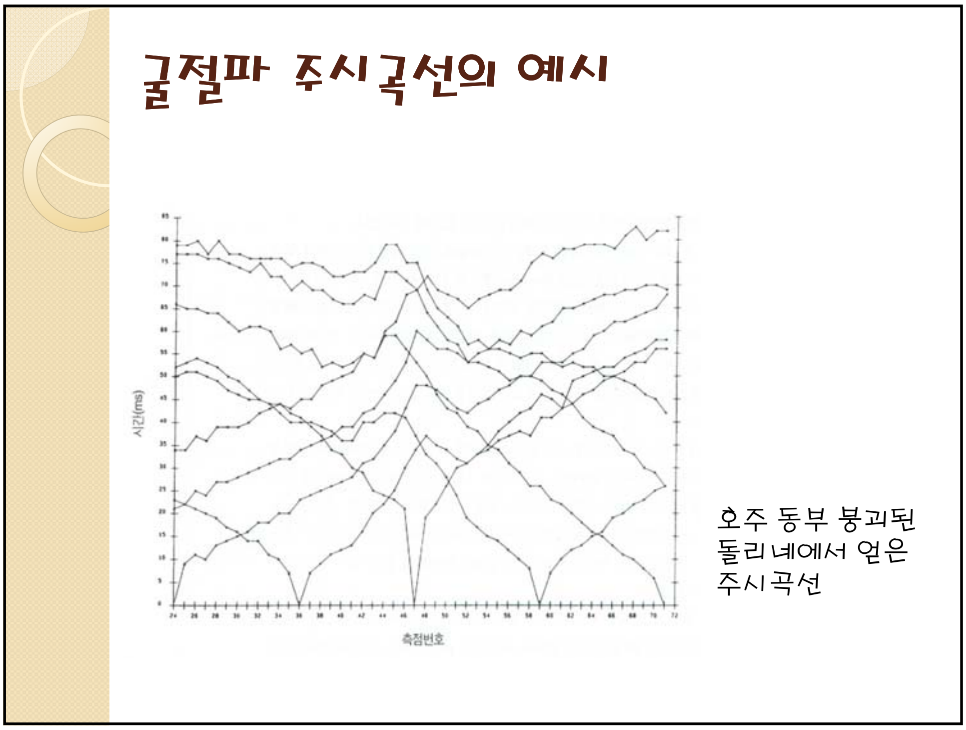


$$T = \frac{X}{V_2} + t_i$$

수평층 굴절파 주시



굴절파 주시 예시

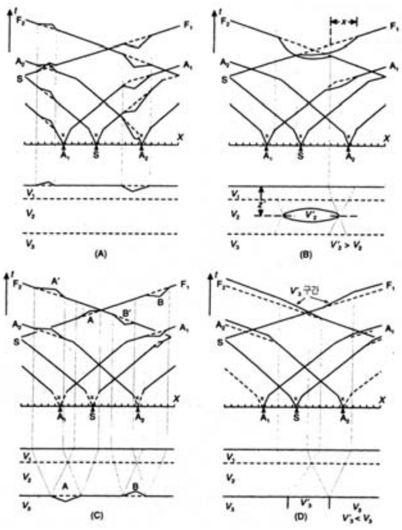


굴절파 주시곡선의 예시

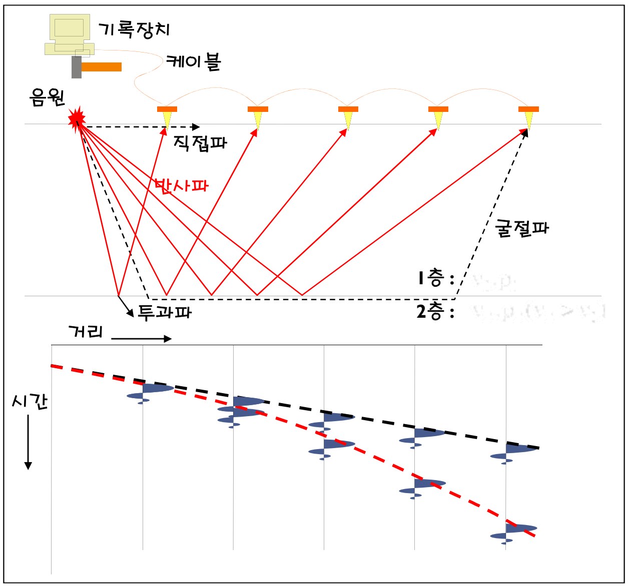
오주 동부 붕괴된
돌리네에서 얻은
주시곡선

주시곡선의 이상

- 초동의 부정확한 발췌로 인한 초동 돌출이상
- 천부의 속도 또는 두께의 변화
- 지표 지형의 변화
- 지중에 다른 속도층 존재
- 국부적인 불규칙한 지형구조
- 굴절면 속도의 수평적인 변화



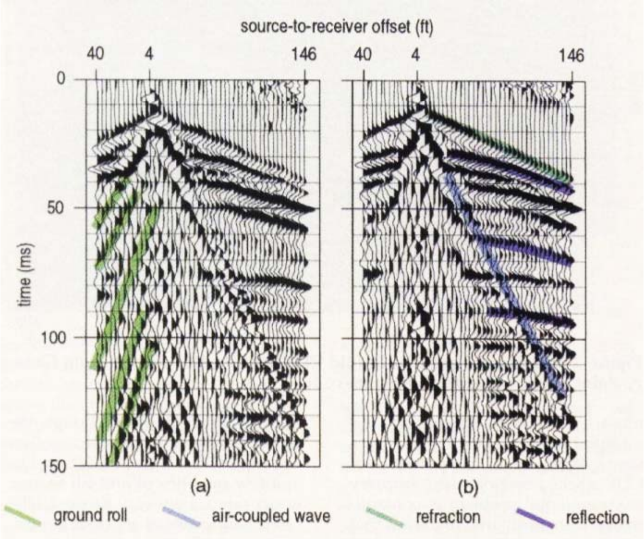
반사파 탐사 모식도



반사파 주시

- 수평2층구조 반사파 주시

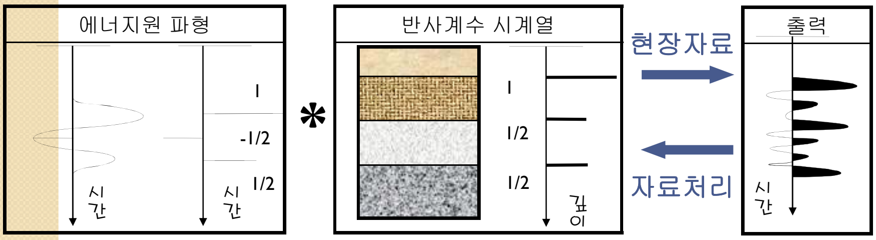
반사법탐사자료 예시



반사계수

- 수직입사에 대한 반사계수

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}$$



자료처리 모식도

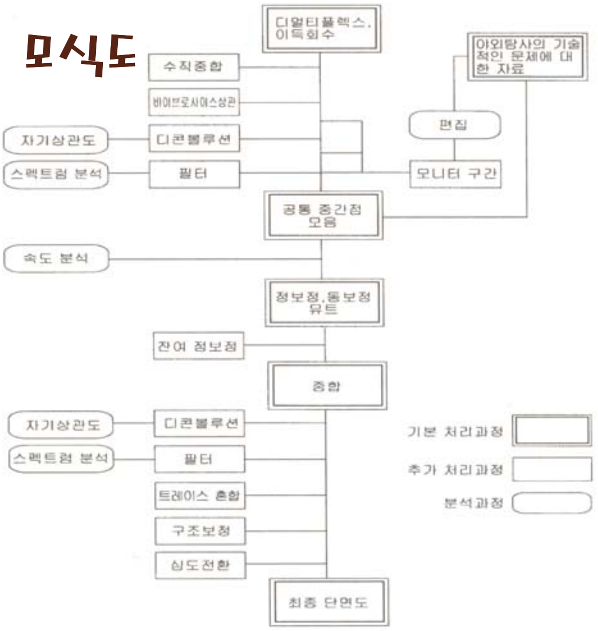
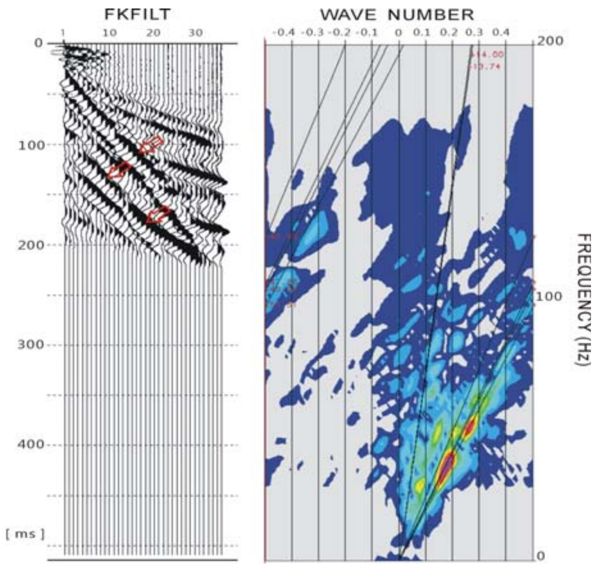


그림 6-32. 반사법 탄성파자료의 처리 및 분석 과정도.

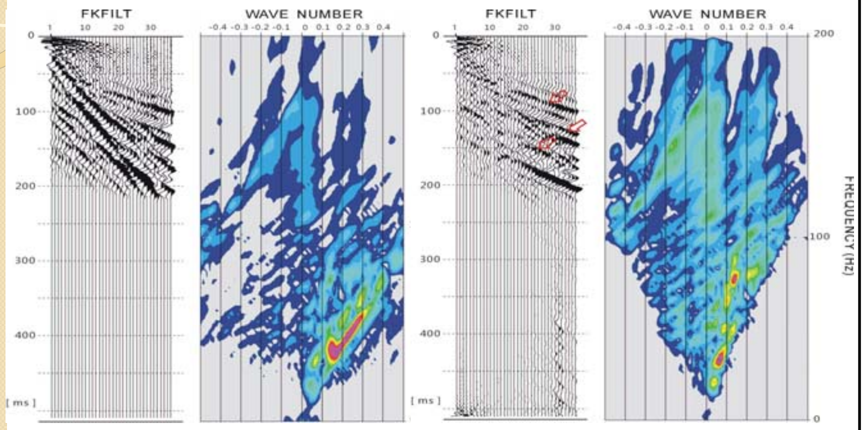
자료처리 모식도

- 탄성파탐사
- 자료변환
- 자료편집
- Geometry설정
- CDP gather
- 뮤팅
- 속도분석
- NMO보정
- 중합
- 디컨벌루션
- 구조보정
- 자료해석

자료처리 F-K filter

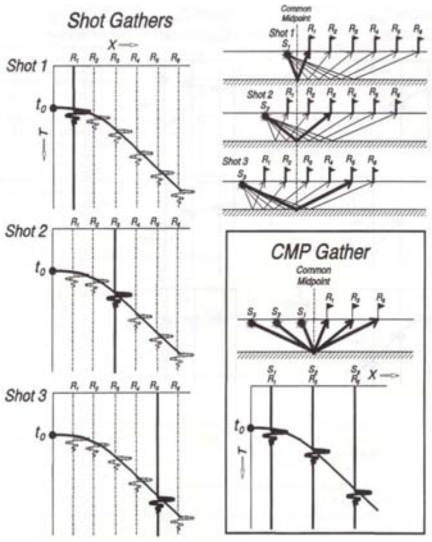


자료처리 F-K filter



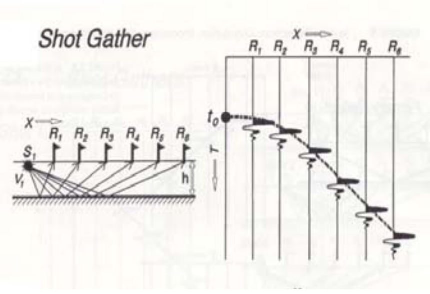
자료처리 CDP gather

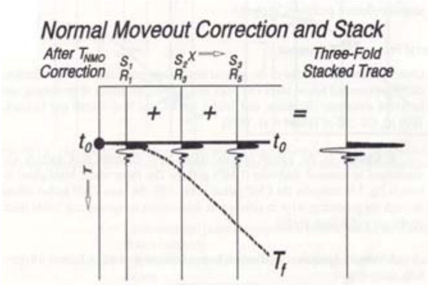
- CMP gather
  - 지하의 각 점이 여러 차례 샘플링 되도록 하여 자료 처리 과정에서 일정한 보정작업과 이들을 합침으로써 신호성분은 강화시키고 잡음은 약화시켜 궁극적으로 양호한 S/N을 얻는 기법
- Fold수 & Coverage

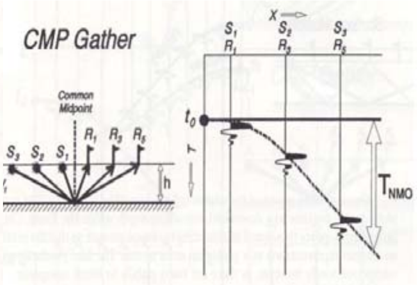


자료처리 NMO보정

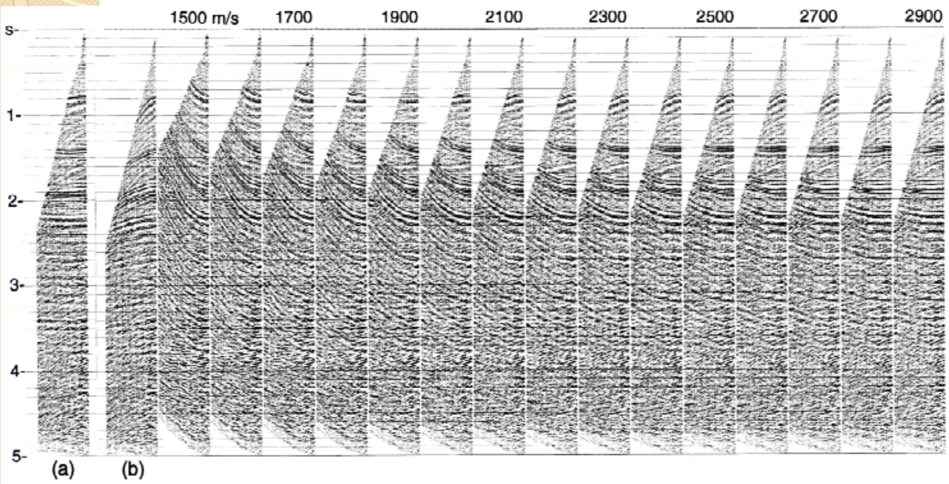
- NMO보정



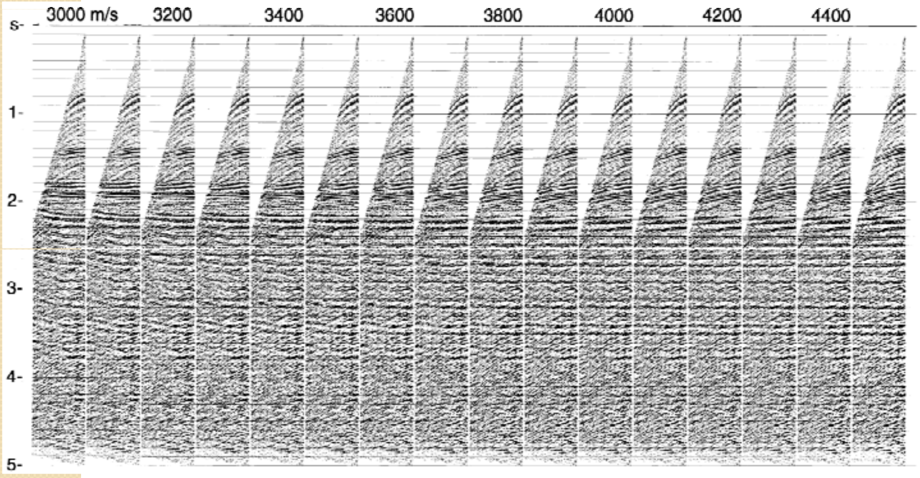




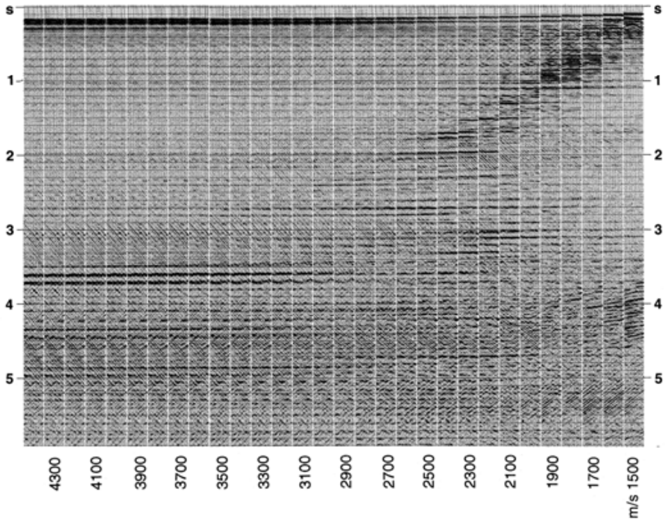
Constant-velocity moveout correction



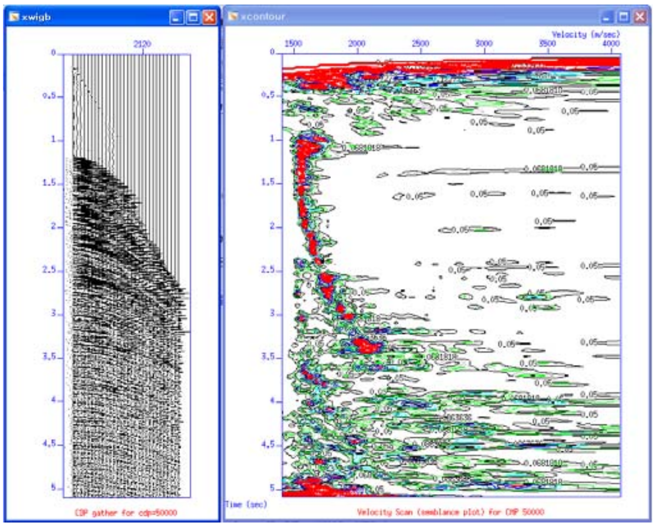
Constant-velocity moveout correction



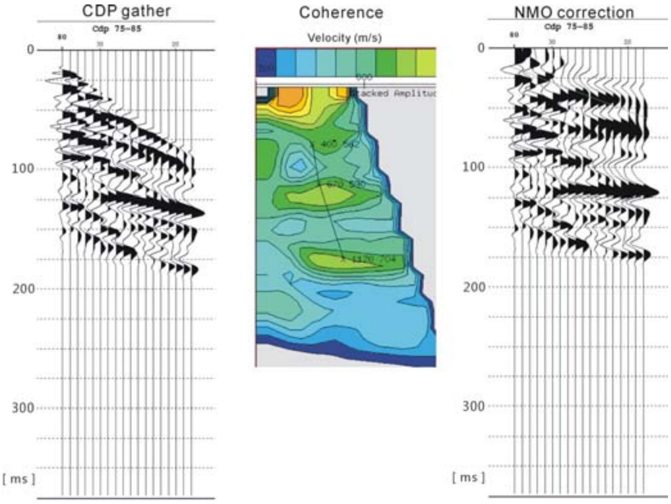
Constant-velocity stacks of 24 CMP gathers



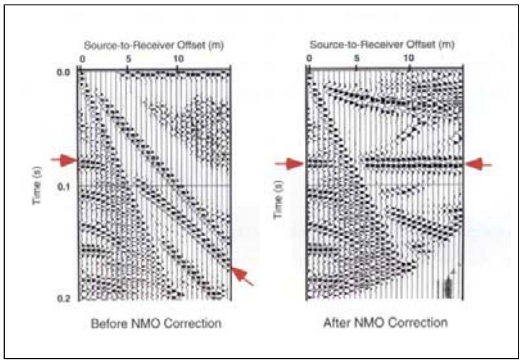
자료처리 속도분석



속도분석 및 NMO보정 예시

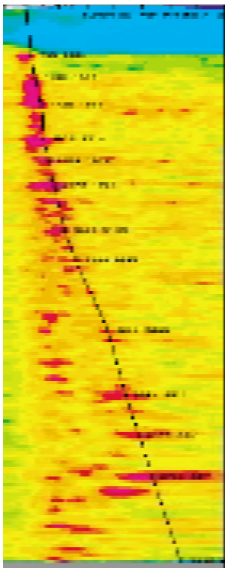


속도분석 및 NMO보정 예시

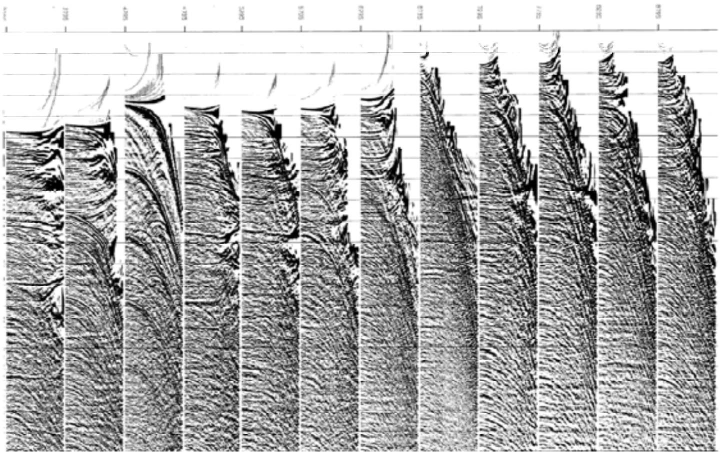


Before NMO Correction

After NMO Correction

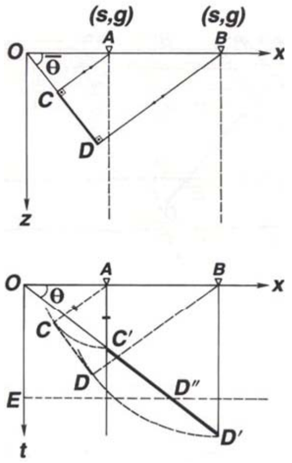


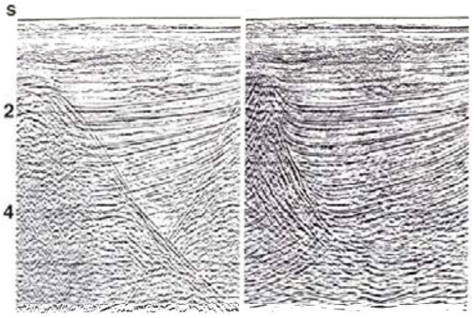
NMO stretches



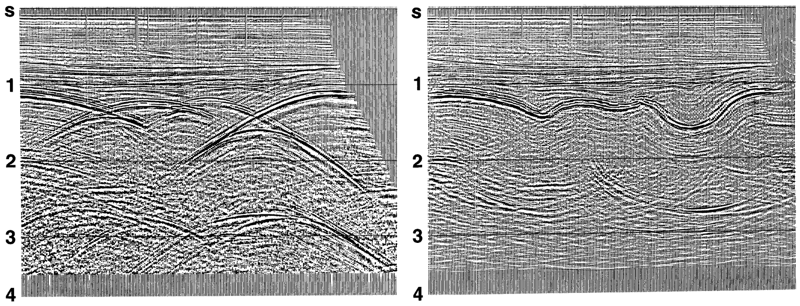
Dix equation

Migration





Migration



(a) (b)

탄성파 자료해석

- 지질학적 고려사항
  - 근원암(Source rock): 탄화수소 생성, 흑색셰일이나 세립질의 흑색 석회암
  - 저류암(Reservoir rock): 탄화수소가 잘 이동할 수 있도록 충분한 공극과 투수성을 가진 암석. 공극률이 높은 사암, 파쇄나 공동이 잘 발달되어 있는 석회암이나 돌로마이트 등의 탄산염암
  - 트랩(Trap): 구조적 트랩 (습곡, 단층, 부정합, 암염돔)과 층서적 트랩 (퇴적환경의 영향)
  - 덮개암(caprock): 집적된 탄화수소가 빠져 나갈 수 없도록 불투수성 암석이 덮고 있어야 함. 셰일이나 증발잔류암
- 석유와 가스가 함께 존재하는 경우
  - 비중에 의하여 가스가 위쪽, 석유와 지층수가 하부에 존재

퇴적구조

- 탄화수소 트랩을 형성하는 퇴적구조

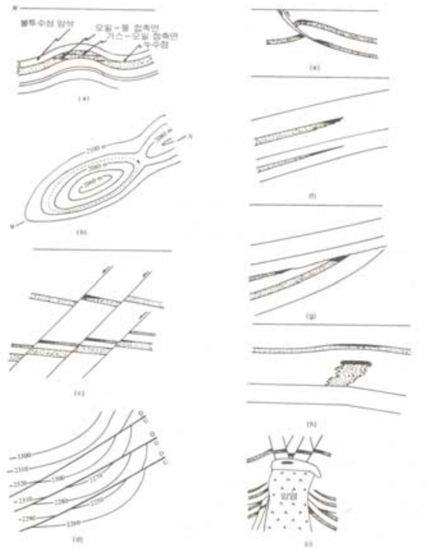


그림 6-185 탄화수소 트랩을 형성하는 퇴적구조
(a) 배사트랩, (b) 배사트랩의 저류층의 상부면에 대한 등심선도, (c) 단층트랩, (d) 단층트랩의 중앙저류층에 대한 등심선도, (e) 드러스트 단층에 의한 트랩, (f) 암상 변화와 첨멸에 의하여 생성된 층서트랩, (g) 부정합 트랩, (h) 석회암초에 형성된 트랩, (i) 암염돔과 관련된 트랩들.

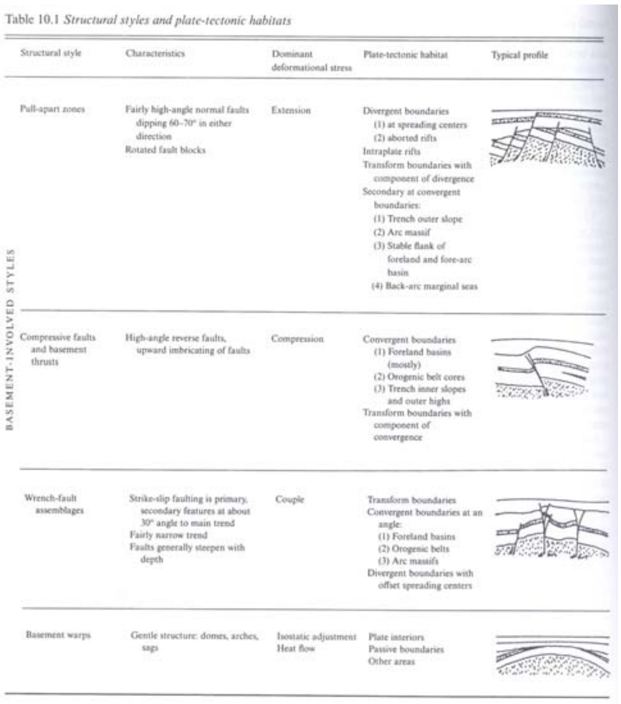


Table 10.1 *Structural styles and plate-tectonic habitats*

	Structural style	Characteristics	Dominant deformational stress	Plate-tectonic habitat	Typical profile
BASEMENT-INVOLVED STYLES	Pull-apart zones	Fairly high-angle normal faults dipping 60–70° in either direction Rotated fault blocks	Extension	Divergent boundaries (1) at spreading centers (2) aborted rifts Intraplate rifts Transform boundaries with component of divergence Secondary at convergent boundaries: (1) Trench outer slope (2) Arc massif (3) Stable flank of foreland and fore-arc basin (4) Back-arc marginal seas	
	Compressive faults and basement thrusts	High-angle reverse faults, upward imbricating of faults	Compression	Convergent boundaries (1) Foreland basins (mostly) (2) Orogenic belt cores (3) Trench inner slopes and outer highs Transform boundaries with component of convergence	
	Wrench-fault assemblages	Strike-slip faulting is primary, secondary features at about 30° angle to main trend Fairly narrow trend Faults generally steepen with depth	Couple	Transform boundaries Convergent boundaries at an angle: (1) Foreland basins (2) Orogenic belts (3) Arc massifs Divergent boundaries with offset spreading centers	
	Basement warps	Gentle structure: domes, arches, sags	Isostatic adjustment Heat flow	Plate interiors Passive boundaries Other areas	

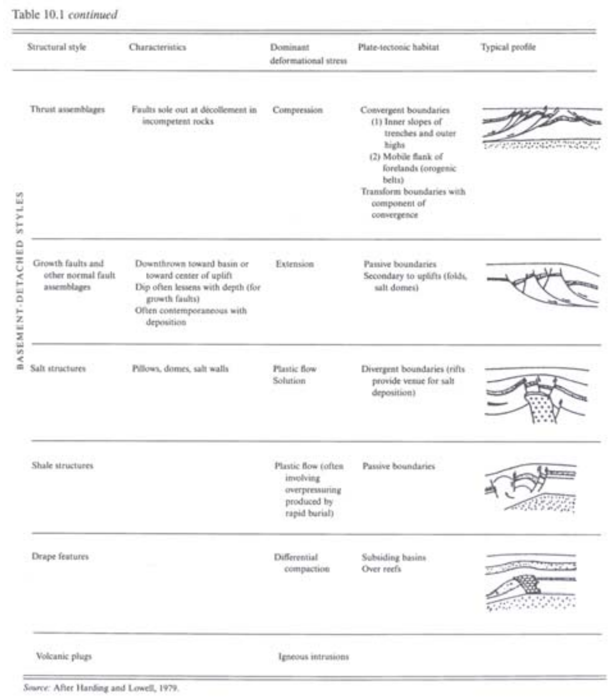


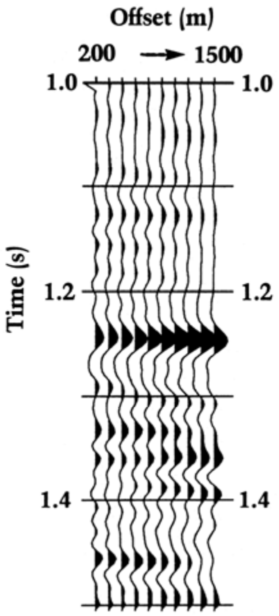
Table 10.1 *continued*

	Structural style	Characteristics	Dominant deformational stress	Plate-tectonic habitat	Typical profile
BASEMENT-DETACHED STYLES	Thrust assemblages	Faults sole out at décollement in incompetent rocks	Compression	Convergent boundaries (1) Inner slopes of trenches and outer highs (2) Mobile flank of forelands (orogenic belts) Transform boundaries with component of convergence	
	Growth faults and other normal fault assemblages	Downthrown toward basin or toward center of uplift Dip often lessens with depth (for growth faults) Often contemporaneous with deposition	Extension	Passive boundaries Secondary to uplifts (folds, salt domes)	
	Salt structures	Pillows, domes, salt walls	Plastic flow Solution	Divergent boundaries (rifts provide venue for salt deposition)	
	Shale structures		Plastic flow (often involving overpressuring produced by rapid burial)	Passive boundaries	
	Drape features		Differential compaction	Subsiding basins Over reefs	
	Volcanic plugs		Igneous intrusions		

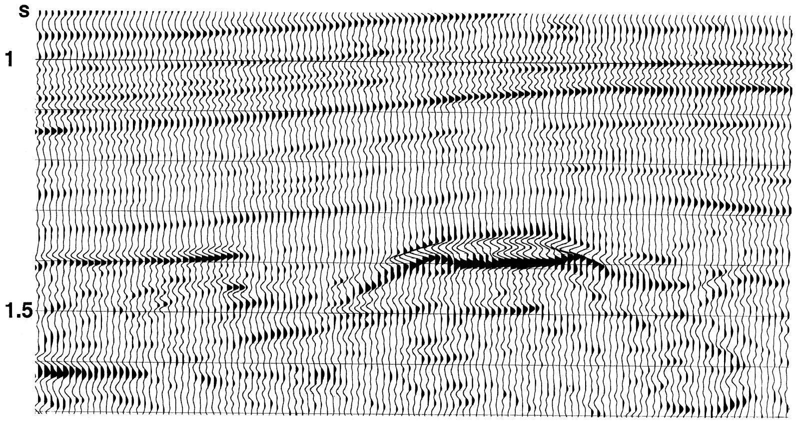
Source: After Harding and Lowell, 1979.

AVO

- Amplitude variation with offset
- Amplitude versus offset



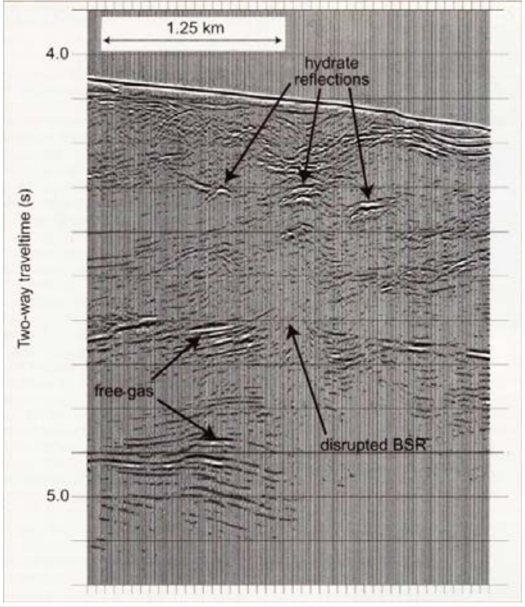
Bright Spot



Gas Hydrate

- BSR

  Bottom simulated reflectors



SH wave source