BASICS OF SEISMIC STRATIGRAPHY

I. INTRODUCTION

A. Definitions

1. Seismology- the study of vibrational seismic waves, earthquakes and the interior structure of the Earth
   a. Earthquakes: naturally occurring seismic event
   b. Nuclear Explosions: artificially induced seismic events, used by seismologists

2. Exploration Seismology = "Applied Seismology"- study of artificially generated seismic waves to obtain information about the geologic structure, stratigraphic characteristics, and distributions of rock types.

   a. Technique originally exploited by petroleum industry to "remotely" sense structural traps and petroleum occurrences prior to drilling

   b. "Remote Sensing" technique: in that subsurface character (lithologic and structural) of rocks can be determined without directly drilling a hole in the ground.

3. Seismic Stratigraphy- use of exploration seismology to determine 3-D rock geometries and associated temporal relations.

   a. General Basis: Seismic waves induced through rock using artificial source (e.g. explosive or vibrational source), waves pass through rock according to laws of wave physics, "geophones" record waves and their characteristics

      (1) Seismic wave behavior influenced by rock type, structure, bed geometries, internal bedding characteristics

   b. "Seismic Facies": seismic wave patterns used to interpret rock type, lithology, structure, bed geometries.

4. Environmental Geophysics: shallow reflection seismic studies can be utilized to identify saturated zones and shallow water table conditions

B. Basics of Seismology

1. Seismic Energy: motion of earth particles
   a. Motion: wave-particles move about point of equilibrium

2. Wave Types
   a. Body Wave: seismic wave travels through body of medium (rock strata)
      (1) P-wave: primary wave = "compression" wave- motion parallel to direction of transport

      (2) S-wave: shear wave: particle motion at right angle to direction of wave propagation

      (3) Wave Conversion: P and S waves can be converted to one another upon intersection with velocity changes of the geologic medium (known as "converted" waves)

b. Surface Wave: seismic wave travels along surface separating two media (e.g. rock and air)

(1) Rayleigh Wave: rolling ground motion, "elliptical roll" wave moving in vertical plane in direction of wave propagation

(a) Responsible for most destruction during earthquakes

(2) Love Wave: horizontal surface motion perpendicular to the direction of wave propagation

3. Wave Physics

a. "Isotropic" Medium: physical properties of medium of equal consistency in all directions.

(1) "Anisotropic" Medium: physical properties of medium of variable character

(a) directionally dependent

b. Wave Front: front of seismic disturbance at which particles begin moving together

c. Ray Path: line perpendicular to wave fronts

(1) Direct path with shortest distance separating two points and lowest travel time

d. Wave Amplitude: maximum wave/particle displacement from point of equilibrium

e. Wavelength: distance between successive points on wave form, measured along ray path

f. Period (T): time for wavecrest to travel one wavelength distance (Units = time)

g. Frequency = 1/T = cycles per time unit

(1) Seismic frequency spectrum

100 Hz = wind, ambient noise; 10-50 Hz induced seismic exploration waves; 1 Hz = Earthquake body waves; 0.01 Hz = earthquake surface waves

Human Ear Range: 20-20,000 cycles/sec

h. Linear Velocity = Distance/Time

(1) Wave Velocity = (Frequency)(Wavelength)

(a) W.V. = function of type of geologic material through which wave passes

i. Spherical Wave: wave generated at a point so that wavefronts would be spherical if in homogenous medium

j. Plane Wave: planar form to wave fronts (spherical wave approaches planar wave form at large distances

k. Wave-interface relationships: as seismic wave travels through medium and encounters a geologic interface (e.g. bedding plane contact between shale and limestone)

(1) Velocity Differences: lithologic interfaces form seismic velocity boundaries representing a transition from one velocity regime to another

(2) Reflection and Refraction

(a) Wave Reflection- portion of wave energy is reflected or "bounced" off of interface back in direction from which wave originated

(b) Wave Refraction- portion of wave energy passes through interface with raypath "refracted" or bent in response to change in physical properties of media above and below interface

i) High Velocity to Low Velocity: wave bent toward line normal to interface

ii) Low Velocity to High Velocity: wave bent away from line normal to interface

(3) Angle of Incidence- angle between raypath and line normal to a velocity interface

(4) Angle of Reflection- angle between reflected raypath and line normal to interface

(5) Angle of Refraction- angle between refracted raypath and line normal to interface

(6) Snell's Law: the sine of the angle of incidence "i" is to the sine of the angle of refraction "r" as their respective velocities of the media: that is:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$ (requires bending of raypaths at velocity changes)

II. HISTORICAL DEVELOPMENT

A. Seismic Studies/Seismic Stratigraphy- like many advanced technological analyses in geosciences, extensively developed since 1960's.

B. Applications and Interpretive Technique developed through 70's

a. Widely used technique by the petroleum industry, the primary tool of the petroleum geologist; along with the drill bit.

C. History of Seismology

1. Earthquake Observations

a. Early quake records date back to 800 B.C.

(1) Chinese Seismoscope: 136 A.D.

(2) 1800's British/European quake observations

(a) Types of seismic waves identified and mathematically described

b. 20th Century Seismologists: Love, Mohorovicic, Gutenberg

(1) Observatories established in early 1900's

(a) data: arrival times and distance from observatory to foci of earthquake

(2) WWII and atomic testing: led to advances in equipment to accurately locate nuclear test sites

c. Current Emphasis: earthquake prediction and prevention

2. Exploration Seismology

a. Robert Mallet, 1848, British Seismologist: first scientist to measure velocity of seismic waves in subsurface rock materials

(1) Seismic Source: black powder explosions; "Geophone": bowl of mercury as detector of arriving seismic waves

(2) Measured velocity of seismic waves through near-surface rock materials

b. Early 20th century applications:

(1) 1912: induced seismic technique for detecting presence of icebergs following sinking of Titanic

(2) Use of mechanical seismographs to detect the position of large enemy guns during WWI.

(3) 1930's: first use of applied seismology to search for petroleum occurrences in Gulf Coast U.S., Germany, and England

(a) Mainly in exploration for salt domes and related "petroleum traps".

c. Seismology and Marine Exploration

(1) Marine Exploration in 1940's
(a) Early: explosive charges with detectors dragged along bottom of ocean
i) Difficulty in locating shot and receiver points geographically

(b) 1950: radionavigation methods advanced, floating streamer cables of "geophones" developed as a consequence of WWII

d. Seismic Stratigraphy

(1) Early Work: identifying subsurface geologic structures (e.g. anticlines, faults, salt domes) associated with petroleum occurrence

(2) 1960's: development of "stratigraphic facies" approach to seismic studies
(a) Use of seismic profiles to interpret lithofacies, stratigraphic geometries, and interpret depositional systems

(b) Developed techniques by petroleum companies
i) much of it "proprietary" and secret squirrel science

e. Modern Developments

(1) Improvements in energy sources and geophone equipment
(2) Advances in treatment and data analysis by computers
(3) Advanced mathematical filtering of data for enhanced seismic interpretation

III. SEISMIC EXPLORATION METHODS

A. Mechanics of Seismic Surveying: inducing seismic waves and recording their behavior as they transmit through the rock medium, nature of the rock medium determined by examining the time-distance-travel relationships through rock strata (i.e. seismic velocity studies as a function of physical rock properties; e.g.

Vel shale < Vel of Limestone)

1. Geologic reconnaissance and mapping/layout for seismic analysis

2. Energy Source (must produce consistent energy release)
   a. "shot holes": drill holes packed with explosives
      (1) Dynamite
      (2) Diesel fuel and ammonium nitrate

   b. "Thumper" 6000 lb weight dropped on ground surface

   c. "Vibroseis": oscillatory vibrator inserted into drill hole

   d. Marine Exploration: pressurized air gun discharged under water

3. Receiving Seismometers
   a. "Geophones" or "Hydrophones": sensitive sound detectors that measure seismic vibrational energy
   b. Connected to computerized data processing center

4. Seismic array: geometric layout of geophones and source locations to properly "sense" subsurface strata and velocity variations

5. Process:

   a. Energy source is triggered at recorded time (To)

   b. Seismic waves travel from source to geologic medium and back to geophone array

   c. Travel time of waves from source to receiver is measured and process
      (1) Travel time = function of
         (a) physical properties of rock medium
         (b) depth of rock medium

   d. Entire process repeated along grid

      (1) Geophone arrays oriented and moved to provide desired coverage during exploration (both horizontally and vertically)

6. Data Processing

   a. Seismic signals and arrival times sensed by geophone
   b. data electronically transmitted to computer
   c. data processed and stored on magnetic tape
   d. Data converted into "analog" cross-sections illustrating time-depth relationships
      (1) wave response of geophone amplified
      (2) data filtered and corrected to remove excess secondary noise interference

B. Refraction Seismic Methods

1. "Seismic Refraction": artificially generated seismic waves are "refracted" or bent at discontinuity surfaces (e.g. bedding planes, unconformities) as they travel downward below the surface

   a. Wave refraction a function of the "velocity" characteristics of the rock medium

   b. Refraction Motion: seismic wave impinges on rock layer at critical angle so that part of the travel path is parallel to bedding in the refractor and then the wave emerges from the refractor at the critical angle to return to the surface and the geophone

      (1) Head wave: refracted wave travelling along the surface of refraction

      (2) The vector path of the wave is dependent upon
         (a) velocity of medium
         (b) dip of bed

2. Depth Relationships

   a. Seismic refractor located at shallow depths: first seismic waves to reach the geophones will be those that travel horizontally through the rocks near the surface

   b. Seismic refractor located at deeper depths: first seismic waves to reach the geophones will be those that refracted back to surface

   c. Depths to formations and discontinuities can be calculated from travel times and wave velocity through medium

   d. Regional refraction surveys from a number of locations can effectively define anticlines and salt domes

3. Refraction Surveys require very large distances between source and geophone

   a. Due to the large geophone-source distances required, refraction surveys have not been extensively utilized by petroleum industry

C. Reflection Seismic Methods: most commonly used method by petroleum industry, forms the basis of modern seismic stratigraphy

1. Reflection Method: waves created by an explosion are reflected back to the surface directly from subsurface rock interfaces (without being diffracted or traveling horizontally along the interface)

a. Requires much shorter source-geophone distances

b. Refraction waves are also generated during the reflection process, however the short source-geophone spacing does not record them

c. Short geophone distances make technique readily applicable for marine seismic surveys with geophone streamers towed behind ships

2. Basic Principle: structure and bedding subsurface rock may be delineated on the basis that seismic waves travel at known velocities through rock materials

a. Wave Velocity varies according to rock type in media, density contrasts of rock

b. Based on direct drilling information: estimations of travel time from source to reflector to geophone can be determined

c. Reflecting surfaces: reflection created by changes in density-velocity relationships of rock strata

(1) Bedding Planes
(2) Lithologic discontinuities
(3) Unconformities

** if rock was totally isotropic, significant reflection would not occur**

(a) Not every bedding surface will cause a readily identifiable reflection

(b) Thinly bedded sequences may create composite reflections from a number of thin bedding planes

(c) Characteristic reflection pattern a function of:
i) lithology
ii) bed thickness
iii) bed spacing
iv) lateral continuity of beds
v) geometry of depositional sequences
vi) structural attitude of bedding planes

d. Depth to Reflector

$$D = (0.5)\ T$$

where D = depth to reflector, T = two-way travel time from source to reflector to geophone

(1) Depths to reflected horizons calculated and plotted on seismic cross-sections

e. As seismic waves travel downward away from source, reflected waves are sent to geophones from successively deeper horizons

(1) As D>, T>

f. Important Caveat: the seismic reflection process is in actually much more complicated than a simple reflection time-distance relationship

(1) Reflective character of subsurface highly complicated with very complicated interference, constructional and destructional patterns of waves

(a) Also, seismic wave velocity inherently increases with increasing depth and increased lithostatic pressure

(2) Given seismic reflection pattern is representing the passage of seismic waves through the media, and not the media itself

(3) Hence, reflection patterns are just that, and are not representing the actual rock strata... it is only "sensing" the strata (as with any geophysical technique)

3. Data Display and Seismic Reflection Cross-sections

a. Data Processing
(1) Time-distance-velocity relationships determined by computer processing

b. Data Display: Seismograms
(1) Seismograms: plots of arrival times to geophones and amplitude of vibrational energy reaching geophones

(2) Time-distance vibrational relationships visually displayed on chart recorder

(3) Seismic Trace: plot recording of seismic motion detected by geophones
(a) Amplitude of trace related to intensity of vibrational movement of geophone as received from reflectors

(b) Strong reflectors will generate a higher amplitude trace than weak reflectors

4. Applications of reflection seismology

a. Identification of structures in subsurface
(1) salt domes, faults, anticlines, strike and dip

b. Identification of stratigraphic relationships

(1) Bedding configuration, depositional structure

IV. REFLECTION SEISMOLOGY AND SEISMIC STRATIGRAPHY

A. Introduction

1. Seismic Stratigraphy: developed by petroleum companies

a. Correlation of seismic reflection patterns to identify depositional sequences, and predict lithology of seismic facies, thicknesses of depositional sequences

2. "Seismic Facies": characteristic patterns as determined from reflection seismology profiles

a. Not to be confused with the actual rock or lithofacies

b. Interpretations of rock are made from seismic patterns, however they are not necessarily one in the same

3. Objective of Seismic Stratigraphy: interpreting stratigraphy and depositional facies from seismic data.

B. Seismic Stratigraphy and Interpretive Parameters (**Refer to attached figures)

1. Reflection Configuration: gross stratification patterns identified on seismic records

a. Parallel Patterns- parallel alignment of reflector patterns (includes sub-parallel to wavy)

(1) Geologic Interpretation: uniform strata and bedding planes; stable platform sedimentation/shelf sedimentation

b. Divergent Patterns: wedge-shaped pattern with lateral thickening and divergence (or "fanning") of reflector patterns

(1) Geologic Interpretation: lateral variation in rates of deposition, progressive tilting of sedimentary strata during sedimentation

c. Prograding Configurations: reflection patterns showing lateral repetition of reflectors (Geologic Interpretation: prograding depositional sequences formed by lateral out-building of strata)

(1) Clinoform Shape-inclined-tangential reflector patterns

(a) Sigmoidal (refer to figures)
(b) Oblique
i) Tangential
ii) Parallel

(c) Complex Sigmoid-Oblique

(d) Shingled
(e) Hummocky Clinoform

(2) Geologic Interpretation: outbuilding/progradation of strata during deposition; lateral progradation from shallow water to deep water (e.g. Delta) or by infilling of channels

d. Chaotic Reflection Patterns-disordered arrangement of reflector surfaces

(1) Geologic Interpretation: penecontemporaneous soft-sediment deformation, fluidized bed flow during natural seismic event at time of deposition, overpressured unconsolidated sediments

(2) Contorted Patterns: soft-sediment slumping and deformation

e. Reflection-Free Patterns: massive reflective pattern appearance

(1) Geologic interpretation: homogeneous non-stratified rock units such as salt domes or igneous intrusives; or very highly contorted strata

2. Reflection Continuity: measure of the degree of lateral continuity of reflector horizons; direct reflection of the degree of lateral continuity of stratal horizons

a. Geologic Interpretations

(1) Continuous Reflectors: widespread, uniform sedimentation patterns
(2) Discontinuous Reflectors: channelized deposits, unconformities, erosionally-truncated deposits, transgressive-regressive coastal sequences

3. Reflection Amplitude: measure of the energy associated with reflected seismic waves

a. > Amplitude, > reflective energy; and vice versa

b. Controlling factors of amplitude
(1) velocity-density contrasts of strata
(a) Amplitude > with > V-D contrast
(2) Spacing between reflecting surfaces
(a) Thinly bedded sequences: may create constructive interference of seismic waves and yield anomalously large amplitude signature

(3) Fluid and Hydrocarbon accumulations: "bright spots" may result due to increased reflective activity from fluid-saturated horizons

4. Reflection Frequency: no. of cycles or oscillations of seismic waves per second
    a. Hertz = Hz = 1 cycle/second
    b. Controlled by nature of the artificial seismic source

5. Interval Velocity: average velocity of seismic waves between reflecting horizons

    a. Controlled by:
        (1) porosity, density, external pressure, fluid pressure
            (a) Velocity > as porosity < (i.e. lithostatic pressure >)

6. External Form: external form of seismic facies; gross three-dimensional geometry

    ** See discussion of seismic facies patterns below **

C. Procedures in Seismic Stratigraphic Analysis: Goal is to use subsurface seismic data to interpret stratigraphic relationships and depositional environments (interpretations include: lithofacies, unconformities, chronostratigraphic time correlations, and depositional history of basin)

1. Seismic Sequence Analysis- process of delineation of "reflection packages" based on reflection patterns, as defined by bounding surfaces and discontinuities

    a. Sequences: stratigraphic units separated by unconformities or correlative conformities

    b. Sequence patterns: based on relationship of reflectors to surfaces of seismic discontinuity (**Refer to attached figures)

        (1) Onlap: reflector patterns sequentially lapped updip onto inclined surface of discontinuity

        (2) Downlap: reflector patterns sequentially lapped downdip onto inclined surface of discontinuity

        (3) Toplap: inclined strata terminate against an upper boundary created by surface of non-deposition

        (4) Truncation (Erosional): inclined strata truncated abruptly by irregular surface of erosion

    c. Seismic sequences on scale of 50-several meters in dimension

2. Seismic Facies Analysis
    a. Seismic Facies Unit: mappable, aerially definable, three-dimensional unit composed of characteristic seismic reflections, differing from adjacent units

(1) Characterized by reflection configuration, amplitude, continuity, frequency, and interval velocity

b. External Form of Seismic Facies (see attached figures)

(1) Tabular Types
(a) Sheet
(b) Sheet Drape
(c) Wedge
(d) Bank
(e) Lens

(2) Mound Types
(a) General Mound
(b) Fan

(3) Fill Types
(a) Channel Fill
(b) Trough Fill
(c) Basin Fill
(d) Slope Front Fill

c. Principal Seismic Facies Configurations
(1) Parallel configurations
(2) Divergent configurations
(3) Progradational configurations
(4) Mounded/draped configurations
(5) Onlap/fill configurations

(a) Channel-shaped fill sequences

3. Sequence Analysis and Global Sea Level Curves

a. Promulgated by Research Group at Exxon in 1970's (Vail et. al.)

b. Uses sequence stratigraphy and seismic facies analysis (reflector patterns) to identify relative sea level transgressions and regressions in near-shore coastal deposits

c. Used seismic reflection sections from around world to correlate "global sea level" patterns

(1) Sea level Rise = measured from onlap reflector patterns

(a) Sea Level Rise: transgressive coastal onlap if sediment influx < than rate of rise

(b) Regressive seaward advance if terrigenous influx > rate of sea level rise

(2) Stable Sea Level: steady facies progradation as sediment infills basin laterally

(3) Sea level fall = measured from seaward shift of reflector patterns

(a) Unconformities develop during sea level low-stands, erosional truncations develop

(b)

(c) Seaward shift of coast onlap patterns