Seismotectonics - Role in Petroleum Exploration

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ABSTRACT: Seismotectonics, the study of tectonic regimes and their stages from seismic data, is an extremely useful tool in understanding evolution of geological basins. Integrated with “Seismic Stratigraphy” technique, it promotes accurate and reliable evaluation of hydrocarbon potentials of basins in general and prospects in particular, for exploration and development ventures.

INTRODUCTION

The AAPG Memoir “Seismic Stratigraphy” application to hydrocarbon exploration, 1977, brought out a significant revolution in seismic data interpretation. For the first time, a synergistic approach was available to the seismic interpreters for an effective study of evolution and evaluation of basins for their petroleum resources. An initial, but important step involved in data interpretation, is the correlation of seismic events, which often can be arduous and ambiguous, especially where the data quality is not adequate. The veracity of these correlations (as in phantoming, delineation of faults and jump ties across them, termination of a reflection against another, etc.), on which data evaluation and ultimately prognostication of petroleum resources are based, largely depends on the experience and skill of the interpreter from his comprehension of fundamentals of tectonic styles and depositional systems. Tectonics, particularly, play a major role and is an imperative step in the overall assessment of hydrocarbon prospects for exploration and development.

Seismotectonics is study of tectonic regimes and their stages from seismic data. In spite of its eminence and importance, there is hardly any worthwhile reference to this aspect of study of tectonics within the overall scope of seismic data evaluation. A rudimentary sketch about seismotectonics and its role in petroleum exploration is outlined here.

TECTONICS

Stress at a point in depth below earth’s surface is a resultant of geostatic stress, pore pressure and tectonic stress. Tectonic stress is the most important element that can be easily inferred from seismic data. Tectonic stresses, due to external geological forces can be 1) tensional (extensional), 2) compressional, 3) shell (wrench), and 4) vertical (shale/salt diapirs). Each of these tectonic stresses has a regime of a variety of associated deformations or structures, many of which, leave distinct fingerprints on seismic data for diagnosis. Some of these are described below.

1. Tensional Regime Structures
   a. compaction / drape folds; inferred from seismic by thinning of time-intervals (sedimentary thickness) on crest of the feature, as compared to that on the flank.
   b. horsts & grabens accompanied by normal faults.
   c. listric & growth faults; listrics are rootless faults, discernible on seismic sections by their gradual lessening of dip with depth till the fault plane merges with bedding plane. Growth faults are synsedimentary listric faults and are characterized by a thicker sedimentary section on the downthrown side.
   d. rollover structures; formed due to differential loading and slipping of sediments on the downthrown side of growth faults, generally in deltaic deposits.
   e. toe thrusts & cylindrical faults; seen at distal end of bowl-shaped (cylindrical) faults due to buttressing forces of sliding masses of shale, in deep basinal part.

2. Compressional Regime Structures
   a. folds; indicated from the order of time interval (sedimentary thickness), on seismic, which is equal or more at crest of the structure compared to that at flanks.
   b. reverse faults, thrusts & overthrusts; thrusts and overthrusts form with and without involvement of basement, as in skin tectonics. An important aspect of thrusts/overthrusts, is the understanding of the overthrow direction, known as vergence, caused due to compressional forces. The determining factors for vergence are topography (gravity) or pre-existing normal faults. Often, normal faults at basement levels can thus be seen continuing upwards to shallower levels as reverse faults, due to reactivation in a lateral compressional stress regime.
3.  **Shear Regime Structures**

a.  enechelon folds; an alignment of fold structures along a linear zone with the fold axes parallel to each other.

b.  wrench faults; with near vertical planes, involving basement.

c.  reverse & thrust faults;

d.  normal faults orthogonal to folds;

e.  grabens & half grabens; formed in preference to horsts.

f.  flower structures; evinced on seismic by near vertical axial alignment of shallower highs over lows at deeper levels or vice-versa.

The wrench tectonic stresses are generated deeper in basement due to horizontal shear couples. The shear process is repetitive and depending on the relative movement of fragmented basement blocks, the wrench can be divergent, convergent, or more simply, parallel. Features like normal vertical faults, grabens and half-grabens and simple flower structures are believed to be associated with divergent wrench, whereas, folds, reverse and thrust faults are commonly ascribed to convergent wrench. Some other wrench indicative features on seismic can be - drastic changes of reflection events and their characters across seismic sections, and convergence of high trends into lows (or vice-versa), juxtaposition of highs with lows across normal faults, and dog-leg patterns of faults (strike-slip faults) discernible on maps.

4.  **Vertical Regime Structures (Diapirs)**

a.  shale / salt diapirs & stretch faults.

b.  residual shale masses & growth faults.

Shale and salt tectonics are similar and are caused due to plasticity of rocks and geostatic disequilibrium provided by density variations. Generically, it belongs to the class of extensional tectonics but has been discussed here separately due to its uniqueness.

Shale and salt growths can be synsedimentary or post-depositional and can be intrusive or extrusive (exposed) in nature. Seismic sections provide excellent clues to unravel the timing and history of these growths. Synsedimentary diapirs are indicated by presence of drapes (thinning of time interval) over it and with near flat events (beddings) at flanks. Post-depositional diapirs, on the other hand, are characterized by sharp upward drag of overlying younger events. Often, collapse structures such as synclines at the flanks, turtle structures and steep dips of overlying events can be seen on seismic caused by withdrawal of mobile rocks from core area, moving outwards.

Intrusive and extrusive diapirs can be interpreted sometimes by their associated faults and their patterns. When the growth diapir is not exposed (intrusive), the accumulated stress tends to dissipate through a number of radial synthetic and antithetic faults at its top, known as stretch faults. In case of exposed structures, however, the accumulated energy gets released through erosion without much fault activity.

Residual shale masses are features mostly formed in deltaic systems due to differential loading of sand and shale. The deformation initially starts with growth faults but evolves eventually to a complicated feature of central mass of shale pillow with a number of faults at flanks and at top.

**BASIN EVALUATION**

Evaluation of hydrocarbon prospects in a basin depends primarily on analysis of its source, reservoir, and trap potentials. Seismotectonics help in proper appraisal of these elements by comprehending evolution of basins and evaluation of its petroleum plays, eventually leading to prognostication of resources. Source potential is assessed from knowledge of sedimentary thickness, its organic content, kerogene type, burial history and geothermal maturity.

Unravelling the tectonic history from seismic can be extremely useful in this regard. Synsedimentary faults and progressive tiltings, interpreted from seismic, as active for long period, are indicative of deposition of thicker sediments under aerobic conditions and of undergoing subsidence to deeper depths for better source maturation. Zones under severe tectonic stresses like hot-spots and junctions can also be pointers to potential areas for favourable geothermal conditions. Rocks with good primary porosities are deposited in high energy environments, often influenced by tectonics. Uplifts, weathering and faults also tend to induce secondary porosities through actions of leaching, channeling, vugs and fractures. Understanding of tectonics, thus, can help predicting prospective reservoir facies. Traps, structural and stratigraphic are, however, results of direct and/or indirect involvement of tectonics and are mapped from seismic.

Assimilation of tectonic styles and its architecture in an area, allows interesting comparison with similar known basins elsewhere in the world and facilitates improved
assessment by drawing from analogies. For instance, recognizing the tectonic style in a geology associated with it. The long period active fault system in a wrench system provides conditions for differential movement of blocks with varying stress, with sinking and tilting of unstressed blocks. This may, prima-facie, be conducive to conditions for deposition of source and reservoir facies, juxtaposed to each other. More importantly, the wrench tectonics produce a variety of important and interesting structures as potential traps for hydrocarbon accumulation.

**PROSPECT APPRAISAL**

Prospects are appraised for their potential commercial values by technoeconomics and risk analysis, before putting up to management for a drilling decision. Vital evaluation parameters, besides the customary aerial extent and amplitude of a prospect, are the associated source, reservoir and seals, entrapment mechanisms to form an effective trap, and more importantly, formation of the trap vis-a-vis the timing of hydrocarbon migration. Comprehending the dynamics of tectonics is extremely important to validate the potential prospective traps such as the anticlines, fault closures, wedges and unconformities for their effectiveness to hold hydrocarbons. Faults, specially, are extremely important in this regard and warrant careful detailed synthesis as they are known to play major roles in migration and accumulation of oil and gas. Proper interpretation of fault properties such as, their delineation, type, age and history, allows to analyze the roles played as seals, leaks or conduits in primary and secondary migration of hydrocarbons. They can also be instrumental in enhancing permeabilities, as in fractured reservoirs. Critical study of faults can even lead to and provide vital information during development phase for better and effective reservoir management.

**CONCLUSION**

Seismotectonics, study of tectonics from seismic data, is extremely useful to enhance interpretation capabilities and is a sine qua non in holistic assessment of geologic basins and hydrocarbon prospects. It is the vital key, not only in evaluation of resources and reserves in exploration acreages in initial stages, but continues to be so, also in later stages, in field development and production.