STRUCTURAL GEOMORPHOLOGY IN PETROLEUM EXPLORATION: GEOLOGIC REMOTE SENSING AND THE SEARCH FOR THE SUBTLE TRAP

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ABSTRACT

Oil and gas exploration is moving into increasingly remote, complex, and poorly-understood regions of the world. Most obvious structures have long since been drilled, and the remaining structural traps are revealed by subtle clues at the surface. Remote sensing technology presents these subtle geomorphic indicators to the geologist; he must then discern hydrocarbon traps among all the surficial features.

There are several aspects to structural geomorphology. The first is to understand the rock types being viewed. There are colors, tones, textures, weathering features, common associations, and deformational styles that suggest specific rock types. Recognizing lithology is important because each rock type expresses structure to different degrees. Another aspect is recognizing dip, which allows one to map anticlines and other traps in areas of outcrop. In areas where outcrops are scarce or non-existent, one may interpret drainage patterns, soil color, tone, and textural patterns, vegetation distribution, moraine patterns, and sand cover to predict the location of "blind" structures. Finally, there are several types of faults that play important roles in creating hydrocarbon traps. Each fault type is associated with a set of distinct landforms.

INTRODUCTION

Much work has been done on processing imagery to enhance information content (see other papers, these Transactions). Work on geologic image interpretation is reported less frequently [1, 2, 3, 4, 5] and techniques for assisting petroleum exploration are rarely reported [6, 7]. Most remaining undiscovered resources are located where traps have no obvious surface expression; they are buried by alluvium or soil, sand, till, vegetation, swamps, or other cover. This paper describes the landforms associated with subtle or "blind" geologic structures.

RECOGNIZING LITHOLOGY

It is usually possible to group surface units into categories based on color, texture, vegetation cover, etc. Since intrusive and metamorphic rocks are of little interest to the petroleum geologist, except as areas to be avoided, we will dwell on sedimentary units. Sandstones tend to be resistant and ledge-forming. The high porosity in sandstones and their resultant soils causes low runoff and widely-spaced drainage. High infiltration rates lead to plant communities with deep roots, such as pines. Sandstones are resistant and brittle and display fracture systems prominently. Gullies have steep sides and flat bottoms. Sandstones exposed around a basin margin can reveal the distribution of a hydrocarbon reservoir deeper in the basin, and may contain seeps.

Shales erode easily because of their small grain size. They form badlands (arid) or gentle valleys (temperate or humid climates). High runoff leads to closely spaced drainage. Joints are not well-expressed because the units are more ductile. Gullies are V-shaped in cross-section, and outcrops are sparse. Shale units are extremely susceptible to landslides. Black shale outcrops around a basin may indicate the presence of source rock. Shales indicate the presence of a seal.

Carbonates tend to be resistant to physical weathering. They are often ledge-formers, and are easily fractured. In arid areas they form sinkholes, have thin soils and steep-sided valleys. In humid climates they develop buttes as well as sinkholes, and the topography is rounded. Drainage patterns are considered "deranged" as a result of ending suddenly in sinkholes. Carbonates can be either source or reservoir for hydrocarbons.

Evaporites such as halite and gypsum exist at the surface only in arid climates because they are water soluble. They are usually light colored. They are of interest in exploration because they form seals, diapirs, and decollements. Dissolution of evaporites by groundwater in the near surface can result in chaotic or synclinal collapse structures.

STRUCTURAL TRAPS

Anticlines, domes, and horsts are important structures in the search for oil and gas. The shape of these structures ranges from circular, as in salt domes, to elliptical, to plunging "noses," to a gentle change in strike. The anticline is commonly expressed as a topographic high at the surface. Just as commonly topography may be inverted, with the resistant layers breached by erosion and the core layers exposed as a valley. It is critical to know whether the reservoir unit or seal has been breached, since this usually means any oil will have escaped or been degraded.

Anticlines are formed by horizontal compression at right angles to the fold axis. These folds may also form as a result of salt movement, sediments draping over the edge of a faulted block, or by compression in a thrust sheet.

Domes may be the result of density contrasts between salt, gypsum, or overpressured shale and high-density cover. The disequilibrium results in upward movement of the low density layer. It can be useful to know whether a structure is formed by diapirism: if the reservoir lies below a low-density layer there is no trap since only units above the diapiric layers are

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affected by doming. If the seal has been broken by faulting, however, one might expect hydrocarbons to migrate into higher reservoirs along the flanks or over the crest of the dome.

Horsts are uplifted blocks bounded on one or more sides by faults. They tend to accumulate hydrocarbons at high corners or a updip fault truncations along their flanks. Horsts can be recognized by their gently-inclined upper surfaces, near-vertical bedding around their flanks, and abrupt changes in strike at block corners.

BURIED FOLDS

Buried, or blind folds occur in areas without outcrops, and require geomorphic evidence to be recognized. Buried structures can be expressed as gentle topographic highs in alluvial cover. One must be careful, however, not to interpret every erosional remnant as a structure. Slight topographic rises can cause a change in vegetation type or density. This is a result of a change in moisture conditions (drier, lighter colored) on the uplift, a change in soil type, or a vegetation change from south to north-facing slopes. In swamps one might see "flying levees" such as at Cutoff field, Louisiana, or cane stands in otherwise water-covered areas [8].

Blind structures can be associated with color or tonal "anomalies." These areas are different from background because older material or a lower soil horizon is exposed by erosion within the uplift.

Streams in alluvial terrain may show a marked angularity over buried structures. Fractures propagating upsection due to reactivation, or caused by bending due to drape, exert control on stream channel erosion forming abrupt, nearly right-angle bends.

Areas formerly covered by continental ice sheets contain till and moraine cover. Receding glaciers melted last on topographic highs, since meltwater flows through and speeds melting in low areas. Stagnation moraines formed over pre-glacial topographic highs (structures) in the Williston Basin [9].

In areas of thin sand sheets topographic, and perhaps structural highs tend to be windswept and clear of sand cover. Thicker accumulations occur on the leeward side of the high [10]. The high acts as a windbreak, slowing air velocities and causing sand to drop out. Safir dome, Yemen, and the El Borma field, Algeria, appear as wide, smooth depressions between sand dunes.

Stream patterns are especially sensitive to changes in slope in low relief areas. Channel width/depth ratios increase as gradients flatten over a structure. A channel will narrow and become incised as it passes over a structure. Meanders will develop on the lower gradient, and the stream will straighten downstream of the fold as the gradient increases. Foster and Soeparjadi [11] used this technique to map oil-bearing pinnacle reefs in the Salwati basin, Indonesia. One may observe alluvial ponding and braided streams as the gradient decreases. Lithologic mapping based on drainage texture (coarse in sandstones; fine in shales) has been used successfully to locate folds in the Ucayali basin, Peru [12]. Domed, stratified uplifts are characterized by radial and annular drainage. The deflection of parallel streams in opposite directions can be evidence of a subtle buried structure.

STRUCTURES ASSOCIATED WITH FAULTS

Normal faults provide updip fault closure traps as well as traps at the high corner of tilted blocks. Accommodation zones are saddles formed by the overlap of normal faults. These saddles serve both as depocenters and can be the location of fields (e.g., Morgan field, Gulf of Suez). Normal and reverse faults are often near-vertical at the surface, are characterized by a linear trace, and are frequently indistinguishable. They are identified by an escarpment, offset landforms, by juxtaposition of differing lithologies, or an abrupt change in strike or dip across the trace. Where there are no outcrops, or they are covered by vegetation, near-vertical faults may appear as vegetation or soil tone alignments, often because of near-surface groundwater. Linear stream segments or linear valleys extending several kilometers suggest fault control, since the broken rock in the fault zone is readily eroded into valleys. Alignments of springs reveal groundwater ponding against a fault.

Listric normal faults tend to be arcuate or scoop-shaped in plan view. Faults concave toward the downthrown side are probably listric [13]. Rotation of bedding and continued faulting leads to a sequence of steep to shallow dips as one proceeds basinward. Growth faults, a type of listric fault, are characterized by dip reversal into the fault (rollover). An anticline is formed by collapse of the hanging wall as it slides away from the footwall. The slip on these faults allows thick sands to collect on the downthrown side which, if covered by shale, often trap hydrocarbons (e.g., Gulf Coast Tertiary).

Reverse faults bound many uplifts. A linear mountain front with parallel zones of fractures and faults within the uplift suggest the uplifted block is bounded by reverse faults and overhangs the basin. These parallel zones are probably relaxation features that developed following uplift [14]. The fault and uplifted basement can form an updip seal ("overhang play").

Strike-slip faults are recognized by a consistent lateral offset of units, streams, alluvial fans, roads, etc. En echelon folds develop at 30-45° to the fault and perpendicular to the maximum horizontal compression. The Newport-Inglewood trend in the Los Angeles basin has produced much oil from en echelon folds [15]. Strike-slip faults can also be recognized by pull-apart basins or sag ponds at releasing bends, and by buckle folds and "flower" structures at restraining bends. Pull-apart basins can form depocenters that accumulate source and reservoir units; flower structures often contain folds that trap hydrocarbons.

Thrust faults commonly develop hanging wall folds that contain oil or gas accumulations. These folds tend to be highly asymmetric and are often overturned and/or faulted. Thrusts are difficult to recognize as the trace of a thrust is irregular, following topographic contours rather than cutting across them.

Indications of thrusting include repeated section and abrupt changes in strike or dip representing different structures in the hanging wall and footwall. The hanging wall is often topographically higher, and the fault runs near the break in slope at the base of the upper plate. Where there is no relief across the fault, the hanging wall can be recognized because the strike of bedding is parallel to the thrust front and bedding dips parallel to the thrust fault. In many cases the fault trace is convex in the direction of transport. Leading-edge anticlines characterize thrusts that terminate by ramping upsection. Hanging wall folds tend to have common asymmetry verging toward the foreland. They often form imbricated anticlines or synclines. Detachment folds tend to have amplitudes greater than a quarter wavelength; the axial length is generally several times the wavelength, and the folds are frequently sinuous. Several great oil trends exist in thrust belts, including the Idaho-Wyoming and Canadian overthrusts.

CONCLUSIONS

Structurally trapped petroleum accumulations often occur in remote, rugged, or poorly-mapped terrains, and untested traps are not always obvious at the surface. There are numerous clues to structure that can be observed both directly (e.g., fault offsets, dips) and indirectly (e.g., drainage alignments, vegetation and soil tone changes). Exploration can be done more accurately, faster, and for less cost if remote sensing imagery is interpreted by someone familiar with the subtle signs of structure.

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