

# AIRPHOTO AND SATELLITE IMAGERY LINEAMENTS AND HYDROCARBON EXPLORATION

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Airphoto mapping in the northeastern portion of New Zealand's East Coast Basin reveals the presence of prominent lineament sets. These are more clearly defined by SPOT satellite imagery. The implications of lineaments in terms of data pertinent to hydrocarbon exploration are considered.

Lineaments have been recognised worldwide from airphoto mapping and even more dramatically with the advent of satellite imagery. It has been convincingly demonstrated that many of these structures are related to basement tectonics. The pervasive character of such basement features is well documented and their effects on later structural and sedimentological events throughout the Phanerozoic are often very clearly shown.

Examples of the relationship existing between geological patterns and lineament trends are cited from the Middle East where much sub-surface and extensive surface outcrop data are available. There it has been shown that facies trends, structural anomalies, salt diapir alignments and the definition of enhanced fracture production zones over carbonate reservoirs are commonly coincident with pervasive basement lineament trends.

Little is known of sub-surface structure and stratigraphy in the East Coast Fold Belt of New Zealand. Based on the results of study from other areas the presence of fold trends anomalous to the NE-SW trend of late Tertiary folding suggests the influence of control by deep seated structures. The major lineament set trending E-W to WNW is cause for speculation as to the mode of late Cretaceous and early Tertiary structures and facies distributions. The presence of active oil and gas seepages along two major lineaments of this set is highly significant.

## INTRODUCTION

Photogeological mapping carried out over an area in the northern portion of the East Coast Basin, North Island New Zealand reveals many geological complexities. Complexity of structure in the form of opposing or anomalous fold trends are present and there are indications of subsurface structural disharmony consequent on the presence of plastic intervals in the stratigraphic section.

Superimposed on the surface geology is a simple pattern of photo lineaments with trends in three main directions. These features which at first were plotted from 1:50 000 scale stereo pair air photographs, are even more clearly shown on the SPOT satellite imagery coverage of the area (Fig. 1). Some implications can be suggested as to the relation between remotely sensed lineaments and surface derived geological data. In the absence of sufficient sub-surface geological detail, however, the in-depth meaning of these features is conjectural only. By referring to studies carried out elsewhere in the world as models, it is possible to assess the lineament patterns in a more objective manner and recognise their origins in pervasive, fundamental basement structural fabrics.

## BASEMENT TECTONICS

In 1972 Gay clearly showed aeromagnetic maps covering large areas of North America to be characterised by elongate linear trends which he termed *aeromagnetic lineaments*. Over extensive areas the lineaments fell into specific strike sets. Of particular significance were observations in parts of Utah where the lineaments in fact coincided with faults in the basement which dated back 1.7 billion years. Subsequently, many worldwide studies have confirmed the ubiquitous presence of such basement fracture systems as surface lineaments in the sedimentary cover. Baars (1983) contends that once established, the fundamental structural fabric of the earth has remained constant '*only to be modified and reactivated by the myriad of 'orogenies' that are well known to historical geologists.*' The universally recognised lineament regimes have, by constant reshuffling, been propagated through the sedimentary cover to be manifest at the surface and recognisable on air photos and satellite imagery. Economically the impact of this revelation has been in the recognition of the consequences of the pervasiveness of basement tectonics leading to the control and/or modification of sedimentary patterns and the localisation of mineralised zones, petroleum deposits and even water, along preferred trends. It is puzzling that the basic basement tectonic fabric universally recognised in predominant near NW and NE trend alignments has survived the continental displacements ascribed to plate tectonics.

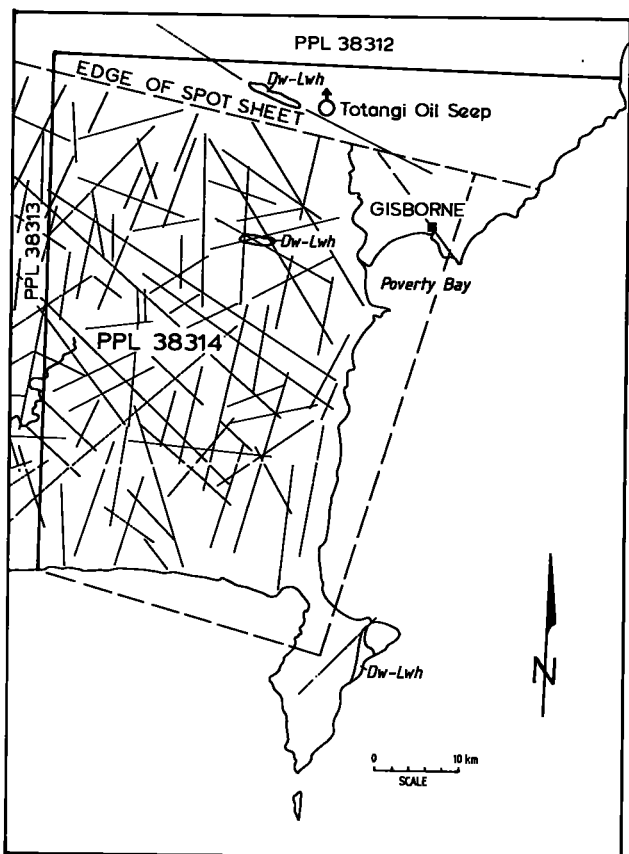


Fig. 1: Lineaments plotted from SPOT satellite imagery coverage of PPL 38314, northern east coast basin, New Zealand.

## FRACTURE PATTERNS

Long before the worldwide recognition of the relationship between surface lineaments and basement tectonics, rock fracture patterns had caught the attention of many geologists. As early as 1911, Hobbs was able to relate patterns of lineaments to repetitions of landforms and structures. Others followed with similar results. Fracture genesis mechanisms including earth tide stresses and diagenetic processes have been suggested as alternatives to orogenic fracture initiation.

Marchesini *et al.* (1962) published the results of an air photo study of fracture patterns over the geothermal area of Larderello, Italy. There, fracture density maps were successfully used in the location of drilling sites for high steam production. Soon after, the present author was involved with the study of rock fracturing in the Oligo-Miocene aged Asmari Limestone, the main reservoir for the oilfields in the Zagros Range foothills of southwest Iran. The 300 to 360 m thick limestone is folded to form traps with huge oil columns. These can be as thick as 1800 m in fields with recoverable reserves in the order of 8 billion barrels of oil (Fig. 2).

Well productions in excess of 500 000 barrels of oil per day are often realised from open hole completions sometimes from only a few metres of drilled section. Such productions are not compatible with the low, 7 to 10 % rock porosity of the limestone. Rather it is largely dependent on fracture porosity and permeability.

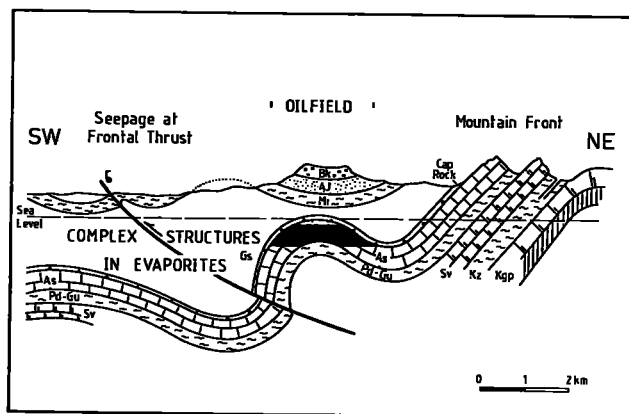


Fig. 2: Typical cross section of a SW Iran oilfield. The variable thickness of the incompetent Gachsaran Formation results from plastic flow within the evaporites it contains. Bk: Bakhtyari Fmn., AJ: Agha Jari Fmn., Mi: Mishan Fmn., Gs: Gachsaran Fmn., As: Asmari Fmn., Pd-Gu: Pabdeh-Gurpi Fmn., Sv: Sarvak Fmn., Kz: Kazhdumi Fmn., Kgp: Khami Gp.

In many cases the Zagros Fold Belt presents the unique situation in which exposed Asmari Limestone structures form folds complementary to their buried oilfield counterparts. These *exhumed* structures allow the examination of rock fracturing at *on-the-ground* scale.

The processing of fracture data collected from extensive observations over several structures in various structural settings led to the conclusion that the density of fracturing at that scale is constant for a given lithology and bed thickness. The fracture spacings have an inverse logarithmic relation to bed thickness (McQuillan, 1973). Although this data provided reservoir engineers with figures pertinent to imbibition calculations for drainage of oil from the limestone blocks comprising the reservoirs, they did not offer any solution to the problem of production variations over the reservoirs in the same rock.

To further investigate the problem, air photo lineaments from several exploited oil fields were plotted. It was expected that the lineament densities and orientations would be related to the north-west-southeast surface structural grain of the region. Such was not the case; rather a three set pattern with trends of NNE and NNW and near E-W was evident. That is to say, lineament trends with no apparent relation to the Late Pliocene compressional fold axes were present. An appeal was made to a mechanism involving the propagation of basement structural fabric through the overlying 40 000 feet or more of sedimentary cover to form surface lineaments. But production patterns still remained unexplained.

## SATELLITE LINEAMENTS AND OIL PRODUCTION TRENDS

The oilfields of Gachsaran and Bibi Hakimeh lie adjacent to one another and their axes parallel the regional strike of the Zagros Fold Belt. Both fields have been extensively drilled and rank amongst some of the world's largest producers. The most recent data available indicates daily productions of 767 000 barrels (Gachsaran) and 245 000 barrels (Bibi Hakimeh), (Tiratsoo, 1984). Production rates from wells show marked variations but they may be grouped in areas of very high and very low or non-economic yields (Fig. 3).

These variations cannot be explained by variations in rock type nor on the wells' positions on the reservoir structures.

Reference to air photo lineament analyses from the surface over these structures confirms the presence of the three set pattern of lineament alignments referred to earlier. When well production patterns are compared from both fields it is apparent that high production areas can be related to either the NNE or NNW trends (McQuillan, 1985).

The first unmanned satellite imagery coverage of the earth's surface was made in 1972 by NASA's Landsat 1. Subsequent Landsat coverage by Landsat 2, 3, 4 and 5 is now available. Examination of Landsat imagery coverage of an area of the Zagros Fold Belt including the Gachsaran and Bibi Hakimeh fields reveals a pattern of lineaments (Fig. 4). This corresponds to the air photo data derived earlier. It is significant that where two NNW trending lineaments cross the two oilfields oblique to the northwest axial trends, high production zones are found. Though NNE trending lineaments are visible, none of these appear to cross the two oilfields considered. The production mechanism in this instance is considered to be related to a reshuffling of small scale fractures in the reservoir rock, thus providing for the enhancement of fracture porosity and permeability along a preferred lineament.

### SATELLITE LINEAMENTS AND OIL FIELD TRENDS

A marked contrast exists between structural trends of oilfields to the northeast and southwest of the Persian Gulf. The older, Jurassic and early Cretaceous reservoir structures in the southwest exhibit two trends which correspond to the major NNE and NNW lineament alignments observed in southwest Iran (Fig. 5).

The Saudi Arabian fields have reservoirs in calcarenite limestone members of the middle to upper Jurassic Arab Zone. The Arab Zone contains four shallow marine carbonate shelf cycles grading up into evaporitic phases.

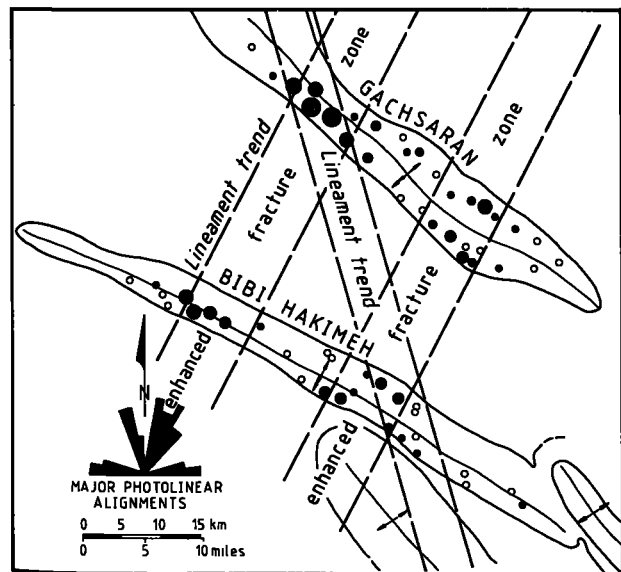


Fig. 3: Oil production patterns over Gachsaran and Bibi Hakimeh fields are related to zones of enhanced fracture porosity and permeability along basement lineaments. Solid circle areas are proportional to production rates. Open circles represent low production wells.

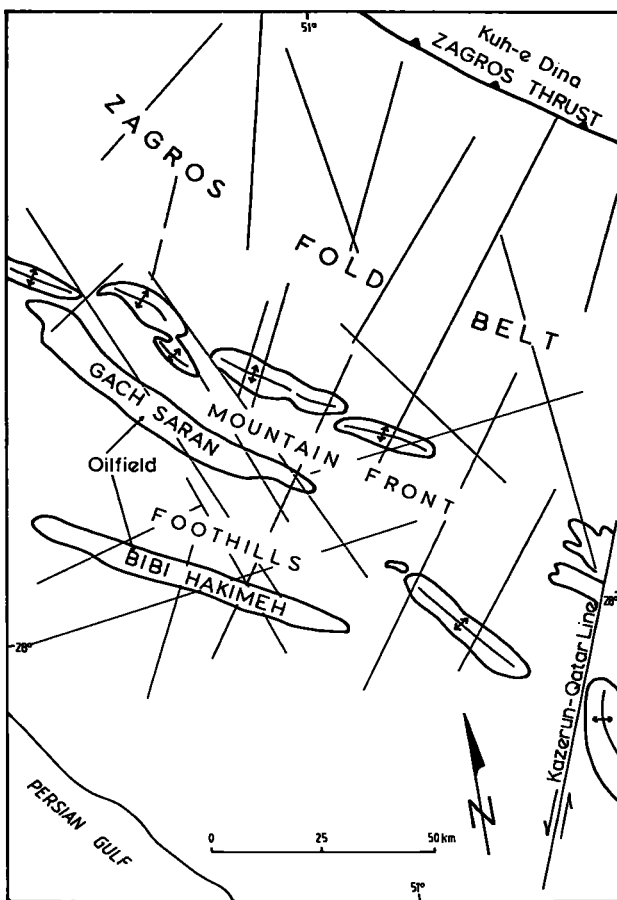


Fig. 4: Tracing from Landsat imagery showing lineaments obliquely crossing oilfield structures on zones of high production.

The reservoir intervals are separated by seals and impermeable anhydrite. Late Cretaceous epi-orogenic reactivation movements along basement trends often accompanied by diapiric salt induced modifications is considered to have provided closure on these structures.

There is a suggestion that within the Saudi Arabian oil field belt, the eastern, middle to upper Jurassic, fields such as Ghawar, have NNE trending axes while the western, upper Jurassic and early Cretaceous, fields such as Khurais have NNW trending axes. However many exceptions to this generalised pattern exist and reservoirs at both stratigraphic levels are present in many of these prolific oil fields.

To the northwest in southern Iraq the NNE trend of oil field axes is most pronounced and consistent in fields such as Rumaila and Zubair, where lower Cretaceous sands form the main reservoir. There also, dome shaped traps in the same reservoir rock indicate the influence of salt diapiric movements.

To the north and east across the Gulf intense late Pliocene folding formed the NE-SW trending folds which contain the Iranian oilfields. It is interesting to note the close proximity of opposing trends in the offshore area containing the Darius (Kharg) Lower Cretaceous NNE trend and the Ardeshir, Oligo-Miocene Ghar, Sandstone NW trend. This seems to confirm the age connotation of lineament associated structures. Cretaceous and older structures are related to basement structural control while the Zagros folds introduce a

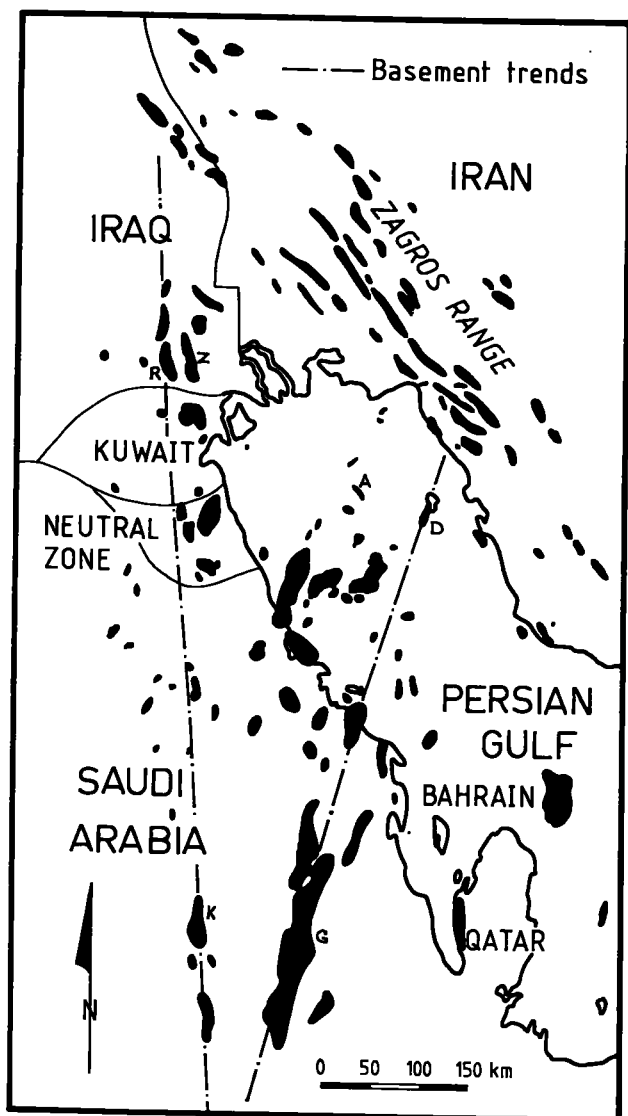


Fig. 5: Oilfields of the Middle East. Jurassic and Cretaceous fields south of the Gulf reflect NNW and NNE basement trends. These contrast with the NW-SE trend of Iran's Tertiary fields. Modified after R. Nurmi (1986). G: Ghawar; K: Khurais; R: Rumaila; Z: Zubair; D: Darius; A: Ardeshir.

late Tertiary NW orogenic grain. Note however that marked modifications to the simple NW-SE trend of Zagros folds occur. These take the form of abrupt bulging or constriction of elongate structures, the rotation or dragging of fold axes especially over plunging noses of the Tertiary folds and the interaction of diapiric related folding with these features along basement related lineaments. Thus, though the Late Pliocene orogenic movements have imparted a strong NW-SW structural grain to the Zagros Fold Belt there persists the structural imprint of the pervasive basement tectonic fabric.

### SALT DIAPIRS AND LINEAMENTS

The Zagros Fold Belt cannot be passed over without some mention of salt plugs. This area of very low precipitation is unique in its fascinating display of more than a hundred extrusive salt domes often with attendant salt glaciers, (Fig. 6). With surface diameters of 3 to 15 km the majority of the plugs lie in the southeastern part of the fold belt, but a few are also present in the northwest along thrust faults and lineament associated wrench faults. The salt contains rafts of

exotic rocks which include Lower Paleozoic sediments and suites of igneous rocks. Kent (1986) when considering the huge size of the exotic rafts within the plugs, suggests that the surface diameters are representative of the vent dimensions. The igneous exotics provide some clue as to the composition of the region's basement rocks which otherwise is unknown from outcrop or drilling data.

The Infra-Cambrian aged Hormuz salt which composes the plugs is nowhere exposed in situ. It has been suggested that the 'Jura-type' folding mode of the Zagros range results from deformation above a basal plastic interval which is provided by the thick and widespread presence of Hormuz salt (Kent, 1968). This concept is corroborated by investigations carried out by Stocklin (1968) to the northeast of the Zagros Range.

Regionally the pattern of extrusive plugs bears no obvious relation to Tertiary structure though many are in fact positioned on the axes of the folds they pierce. In some cases the salt appears to have previously inflated the host anticlines. With the surface extrusion of salt, collapse folds have been superimposed on the larger structures. The presence of other salt diapirs at depth is clear from the many dome shaped modifications to the elongate anticlines, while the dome shape of many of the oilfields in the southern part of the Gulf between Qatar and the Oman Peninsula attests to the diapiric control of deformation there.

Several writers have suggested a rectilinear pattern of salt diapirs in this region. These implied lines of weakness which have been exploited by the plastic salt are related to basement structural trends. Many possible trend directions can be proposed based on plug location alone. However, alignments which correspond to the major basement affiliated trends, described earlier, result when other surface anomalies are taken into consideration, and, as such, lie among satellite lineaments (Fig. 7).

Salt plug movements have not been continuous throughout geological time. This is evidenced by the presence of Hormuz debris in country rocks peripheral to the plugs. These indicate pulses of plug activity to the surface. It is easy to visualise salt islands emerging from time to time to provide localised shoal carbonate facies close to them. Many of the surface exposures of deeper stratigraphy in the salt plug region in fact occur in salt diapir breached structures. Stratigraphic data from such exposures could lead to erroneous data incorporation in regional facies distribution maps.

### SATELLITE LINEAMENT AND FACIES TRENDS

It is beyond the scope of this paper to go into details of the relation between lineaments and stratigraphic variations in the Zagros Fold Belt. However, some of the more significant relationships can be cited (Fig. 8).

An understanding of depositional environments and their control of facies distributions is essential in the search for hydrocarbon accumulations. In particular, knowledge of the trends of potential reservoir and source rock facies is paramount to any exploration venture. When structural and stratigraphic trends can be related to basement pervasive lineaments the usefulness of this as an exploration tool is obvious.

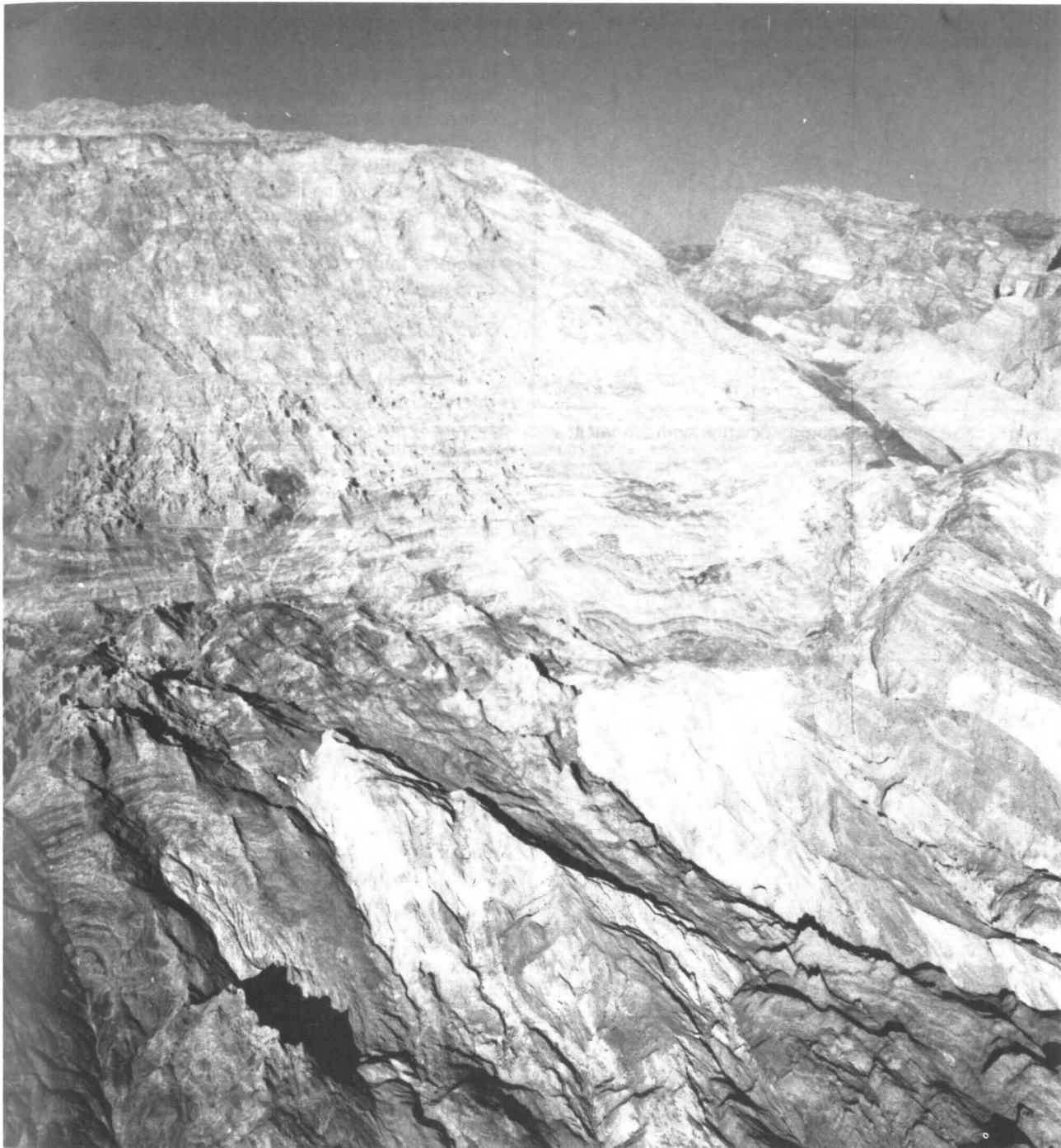


Fig. 6: Kuh-e Namak. A Hormuz salt dome piercing the axis of the Kangan anticline. This active plug has an elevation of 1500 m. Dark coloured rafts on the plugs periphery are trilobite bearing Cambrian shales. The prominent scarp on the right of the plug is Upper Jurassic, limestone Khami Formation.

Shallow neritic and shelf edge carbonates comprise the main oil reservoirs of the Zagros Basin. These include the Oligo-Miocene Asmari Formation, the Upper Cretaceous Sarvak Formation and the Upper Jurassic to early Cretaceous Khami Group.

Carbonate deposition is largely independent of external sediment supply. Generally the sedimentation rate is greater in shallow waters. Such areas tend to spread with time and become shallower while the deeper parts of the basin receive little sediment. Eventually a sharp boundary between the carbonate shelf and deeper water basinal sediments results.

Renewed movements along basement controlled blocks is a mechanism by which such cycles of deposition are initiated. In the SW Iran oilfields sufficient wells have penetrated the Khami Group to enable the determination of the position of a shelf edge over a series of carbonate cycles lying along the trend of a NNW lineament (Fig. 8). This feature extends from the Qatar peninsula through Kharg Island to the head of the Persian Gulf and thence into the high Zagros. Setudehnia (1978) in his treatment of the Mesozoic sequence of southwest Iran maps a persistent shelf edge during Lower Jurassic to mid-Cretaceous time which, in general terms, corresponds to this major lineament. He also includes

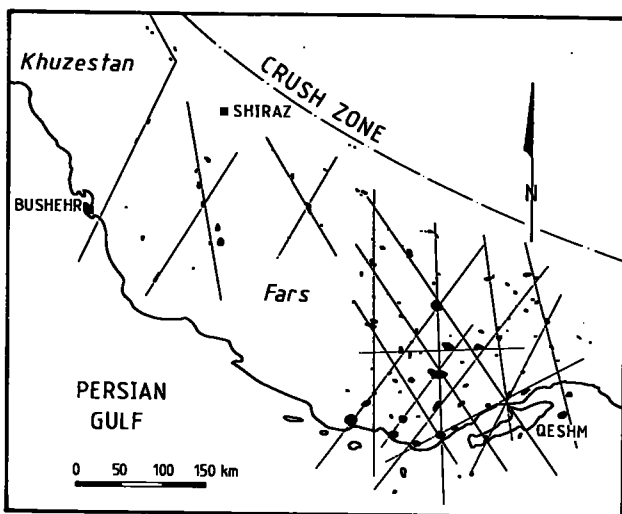


Fig. 7: Salt plugs and their association with basement lineaments, southwest Iran.

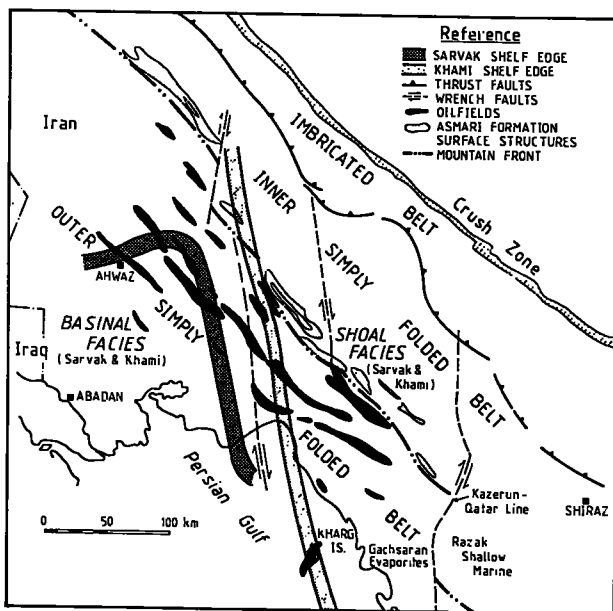


Fig. 8: Part of the Zagros oil field belt showing Khami Group and Sarvak Formation carbonate shelf edges aligned with a north-northwest lineament. The Kazerun-Qatar lineament in the southeast marks an abrupt facies change from Gachsaran Formation evaporites to the Razak Formation carbonates and clastics.

a lithofacies map of the Sarvak Formation which shows a similar, though westwardly displaced, shelf edge trend in the Upper Cretaceous.

The post Asmari restricted environment which led to the deposition of a thick disharmonically folded evaporitic sequence comprising the plastic Gachsaran Formation in the main oil field belt shows an abrupt termination at the Kazerun-Qatar lineament. To the southeast of the lineament conformable shallow water carbonates, marls and clastic rocks of the Razak Formation are the time equivalent of the Gachsaran Formation. Recognition of the relationship between basement lineaments and facies distributions can be invaluable in the planning of exploration programmes.

## SATELLITE LINEAMENTS AND THE NORTHERN EAST COAST FOLD BELT, NEW ZEALAND

From the foregoing it should be clear that basement tectonic trends have an ongoing influence on deposition in and deformation of sedimentary basins. The complications of the northern portion of the East Coast Basin of New Zealand will not be fully understood until more subsurface data from seismic and drilling are acquired. Satellite lineaments however, provide an inexpensive adjunct to exploration ventures in such regions, in terms of their indication of basement fabric control of sedimentary patterns and structural trends (Fig. 9).

Some parallels can be drawn between the Middle East model and the northern East Coast Basin. The stratigraphic section in the latter includes Cretaceous and early Tertiary reservoir intervals, the facies control of which are almost certainly related to basement trends. The Lower Tertiary section contains intervals of incompetent bentonite and montmorillonite clays which provide for disharmony between surface and subsurface structure. It is significant that plastic intervals of these rocks outcrop along the pronounced west-northwest lineament trend while others occur along a north-northeast lineament. These outcrops invariably have a chaotic structure and with their mixed age content of rafts may be likened to the salt diapirs referred to earlier.

The major surface structural grain has a north-northeast trend which corresponds to one set of lineaments. Pronounced anomalies to this, however, are manifest in the near east-west folds of Tokomaru Bay, Anaura Bay and Tolaga Bay. It is considered that these structural anomalies are related to a near east-west to west-northwest trending set of lineaments and could be indicative of structural trends at depth elsewhere in the region. It is significant that the documented oil and gas seepages at Waitangi and Totangi occur along the same lineament trend.

Satellite imagery lineament identification and the recognition of the ongoing effects of basement tectonics when used in conjunction with surface and subsurface data can be invaluable in the more objective planning of exploration programmes.

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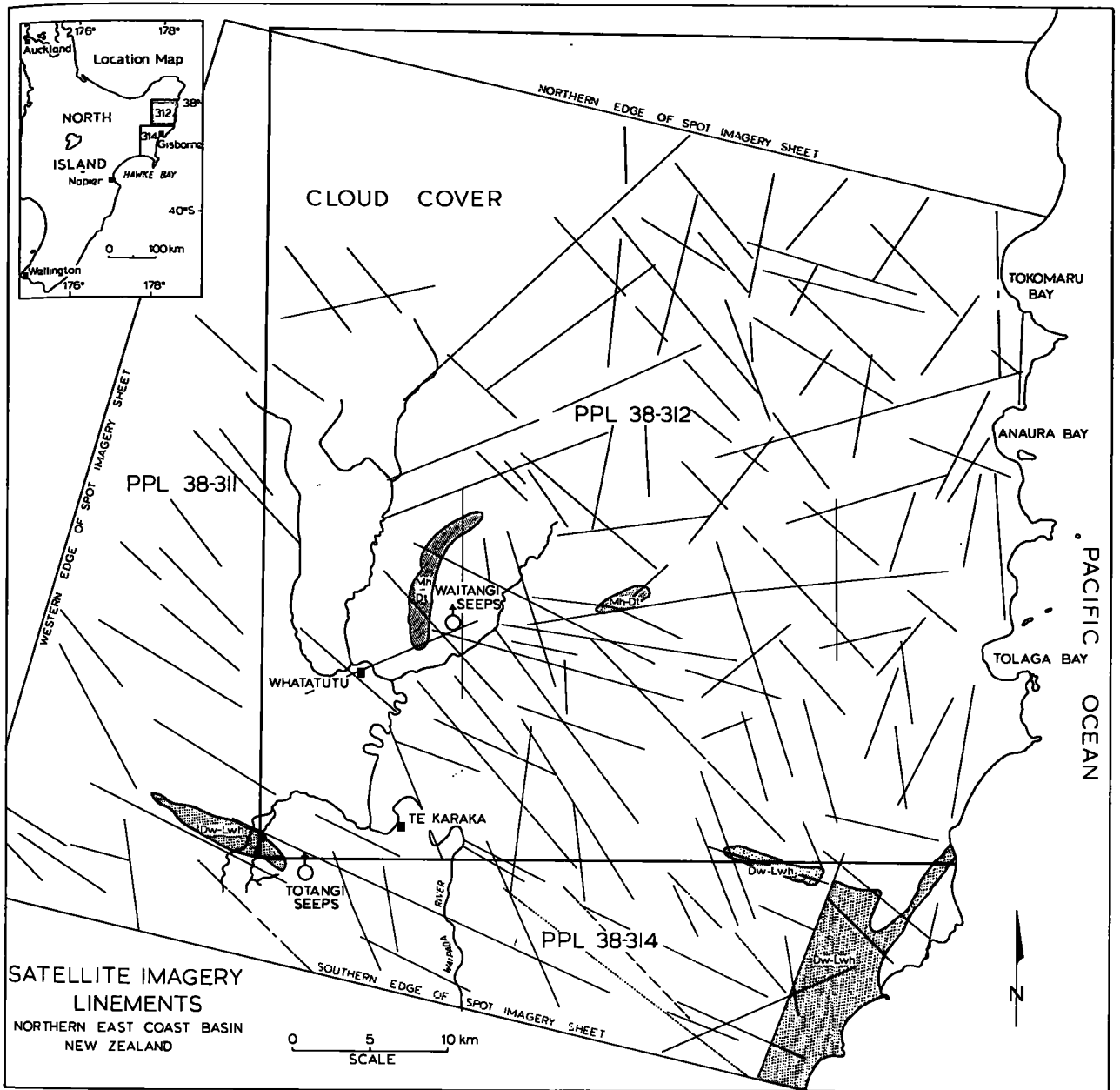


Fig. 9: Lineaments plotted from SPOT satellite imagery coverage of PPL 38312, northern east coast basin, New Zealand.

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