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The Use of Seismological Data to Predict Overpressures

by H. Philippe Bodmer*

Abstract

Seismic valving is a process resulting from gradual build-up of pore pressure due to fluid generation, causing the subsequent opening of a fault along with fluid escape towards surface. This mechanism was recognised causing earthquakes in many parts of the world, as a result of hydrocarbon generation or infiltration of other fluids. Fault orientation is not only a function of external principal stress conditions but also of pore pressure. In this paper it is postulated that focal mechanisms could be used to predict overpressures. This idea could be supported by comparison between focal mechanism interpretation in the Alps of central Switzerland and hydrocarbon exploration data.

Zusammenfassung

Die Generierung von Fluiden im Untergrund, der Aufbau von hohem Druck und das anschliessende Aufbrechen des Gesteines, welches zum Entweichen der Fluide an die Erdoberfläche führt wird als "seismic valving" bezeichnet. Dieser Mechanismus wurde weltweit als Auslöser von zahlreichen Erdbeben anerkannt, sei es als Folge der Generierung von Kohlenwasserstoffen, oder sei es wegen der Infiltration von anderen Fluiden. Es wurde in früheren Arbeiten gezeigt, dass die Orientierung von Bruchflächen nicht nur von den Hauptspannungen abhängt, sondern auch vom Porendruck. In diesem Artikel wird postuliert, dass Herdlösungen von Erdbeben umgekehrt zur Abschätzung von Ueberdruckverhältnissen verwendet werden können. Dieser Gedanke konnte durch den Vergleich zwischen Erdbebendaten und Explorationsergebnissen aus der Erdölindustrie für die Alpen der Zentralschweiz erhärtet werden.

Résumé

La génération de fluides en profondeur crée des surpressions, la rupture consécutive des roches et finalement l'échappement de ces fluides vers la surface. Ce processus appelé "seismic valving" à été reconnu comme étant la cause de nombreux tremblements de terre dans le monde entier, dus à la génération d'hydrocarbures ou à l'infiltration d'autres fluides. Il a été démontré, dans des travaux plus anciens, que l'orientation de failles est non seulement une fonction des contraintes principales, mais également une fonction de la pression interstitielle. Dans cet article, il est postulé que l'orientation des mécanismes focaux de tremblements de terre peut être utilisée pour prédire des régimes de surpression. Cette idée a été appuyée par la comparaison de mécanismes focaux des Alpes de la Suisse centrale avec des données provenant de l'exploration pétrolière.

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1. Introduction

Already in 1959, HUBBERT & RUBEY established the relationship between fault movement and fluid pressure. This concept was further refined by different authors, namely by SIBSON (1981, 1990, 1992), who introduced the idea of seismic valving, i.e. the gradual build-up of pore pressure due to fluid generation and the subsequent opening of a fault along with fluid escape towards surface and related seismicity (Figure 1).

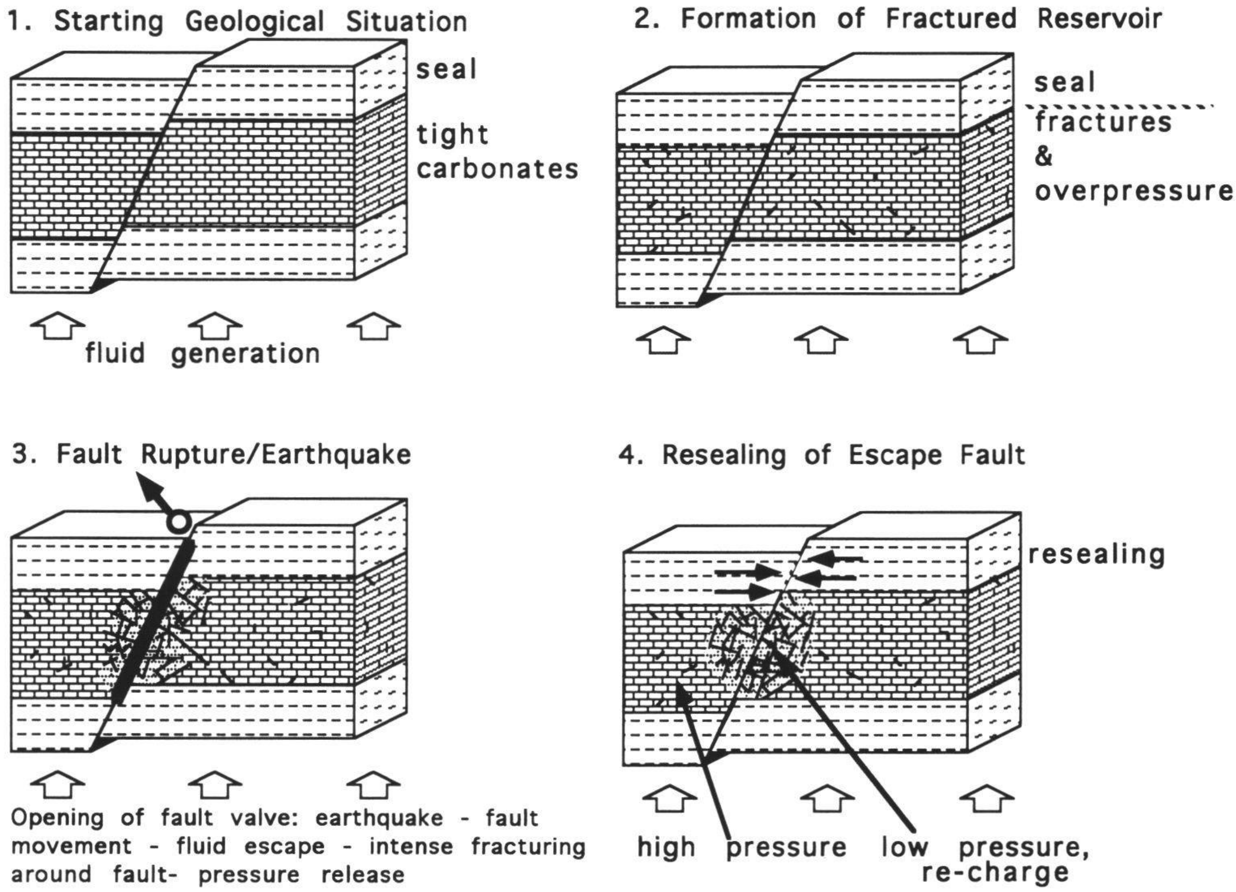

Fig. 1: Schematic model of the seismic valving mechanism.

The opening or reactivation of an existing fault is a direct function of the external stress field, its angle relative to the fault, and pore pressure. Ideally, angles between maximum compressive stress orientation and the fault range between 22 and 32 degrees. Such "favourably" oriented faults can be activated under "normal", hydrostatic pore pressures. The more the angle departs from the favourable orientation, the higher the pore pressure must be to allow for fault opening. In extreme cases (angles of 0 or 53 degrees), near lithostatic pressures must accumulate, provided that the formations can withstand such elevated overpressures prior to hydraulic fracturing. The relationship between pore pressure and fault orientation in a compressional regime is defined as follows (Sibson, 1990, Figure 2):

$$(\sigma 1 - \sigma 3) = \mu_s((\tan \theta_r + \cot \theta r) / (1 - \mu s \tan \theta_r)) \rho_r g z (1 - \lambda_v)$$

where σ1, σ3 are the maximum and minimum principal compressive stresses, μ_s is the coefficient of internal friction, θr the angle between the fault plane and σ1, ρ_r the average rock density, g the gravitational attraction, z the depth and λ_v the pore pressure factor (= $P_f / (\rho_r g z)$, with P_f = pore pressure)

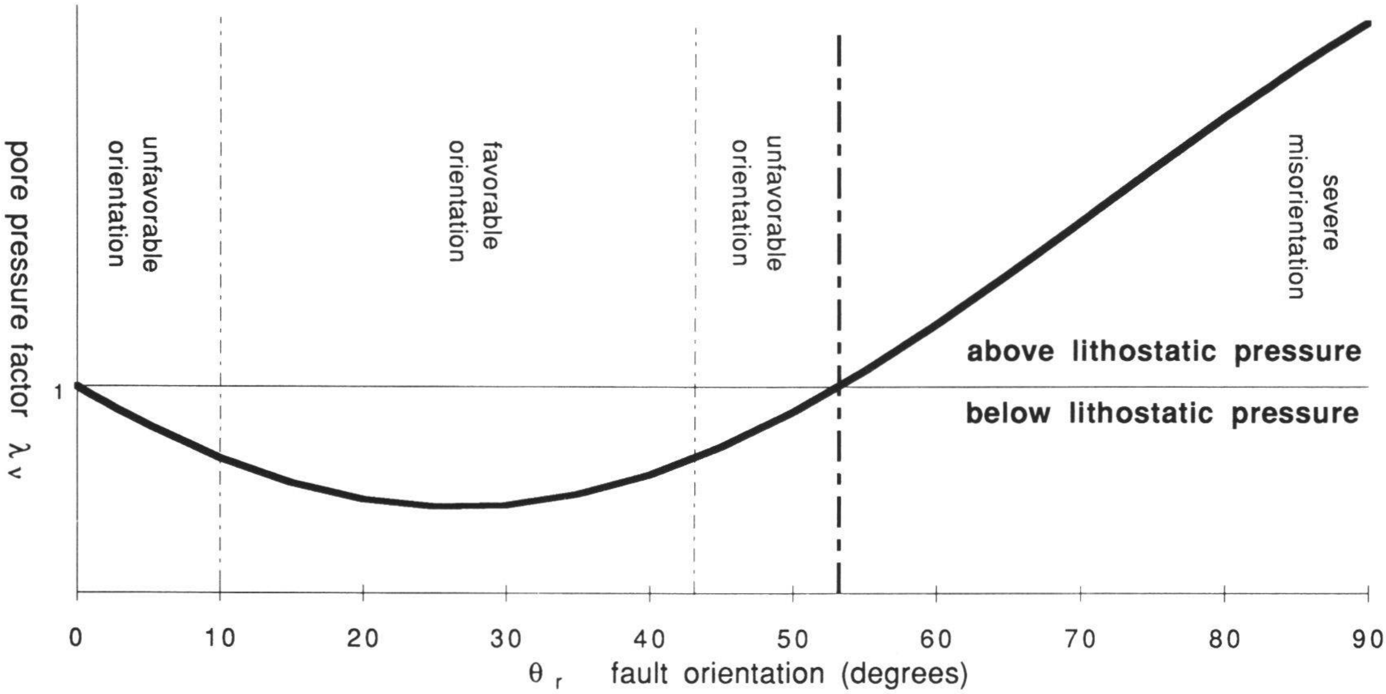

Fig. 2: Pore pressure factor (λ_v) required to reactivate a fault versus reactivation angle θr (angle between the fault and the maximum principal stress σ1) after Sibson (1990).

As opposed to conventional seismology where alternative plane orientations are derived from focal solutions, the proposed method usually provides an unique solution (i.e. the one of the two planes requiring the least pressure to be activated).

When formation pressure meets the condition described by the above formula, failure occurs along the fault, eventually resulting in seismicity and discharge of fluids towards surface. The compartment is re-sealed and pressure builds to another breakout. This episodic process of fluid escape and accumulation cycles is referred to as seismic valving. Many field observations give direct evidence for the concept of seismic valving as documented by the selected references cited below.

2. Observations of seismic valving

Among the innumerable descriptions of phenomena directly or indirectly related to fluid discharge along with earthquake activity, SIBSON (1981) estimates that at least 10^{10} litres of fluids were expulsed in connection with the 1952 Kern County earthquake in California. Focal mechanisms of events after the large 1952 event show distinct local deviation from the regional stress pattern (CASTILLO & ZOBACK, 1994a) which is most probably due to a change of subsurface pressure conditions connected to the main event (see above formula and also CASTILLO & ZOBACK 1994b). Comparable order of magnitude of fluid transport along with seismicity, i.e. in Montana, Idaho and Iran was reported by various authors (see Burley et al., 1989).

Numerous oil and gas fields are known to be associated with faults and geothermal anomalies indicating subvertical fluid flow (MEYER & MAC GEE, 1985, see also BURLEY et al., 1989).

Investigation of cements that partially occlude secondary porosity in Piper Formation sandstones in the Tartan Field and adjacent Witch Graben, UK North Sea led to the conclusion that the deposition of the cements is related to episodically ascending fluid flow from deeper levels (BURLEY et al., 1989). Seismic valving was interpreted to be the most probable mechanism to explain the observations. Diagenetic alterations attributable to the transport of hot fluids were also reported from other areas in the North Sea (JOURDAN et al., 1987). Recent seismicity is lacking in the North Sea area investigated by the above authors and it is thought, therefore, that the process is no longer active.

Fluid inclusion data from hydrocarbon-filled calcite and quartz crystals in alpine clefts provide temperature and pressure information spanning over a time range of several million years (MULLIS 1976 and Figure 3). Temperatures derived from those inclusions in the northern Alps gradually decrease as a result of continuous uplift and erosion. Pressures, however, undergo episodic variations which are attributed to rapid fluid expulsion along with fault opening and slow recharge after re-sealing of the fault valve. Similar pressure variations were also reported from the northern Apennines (MULLIS, 1988).

Luo et al. (1994) published seismological data recorded in the War-Wink field, Delaware basin, USA. Seismicity concentrates near the basis of the overpressure regime where formation pressures are either overpressured or near - hydrostatic (Figure 4, also compare with Figure 3). Note the enhancement of porosity along with increasing earthquake frequency indicating intense fracturing (Figure 1). Also consider that productive formations in the War-Wink field are within the seismically active zone. The seismicity in the War-Wink area also extends into the overpressured zone, a phenomenon which is probably attributable to secondary accumulations of hydrocarbons (see DURHAM, 1994).

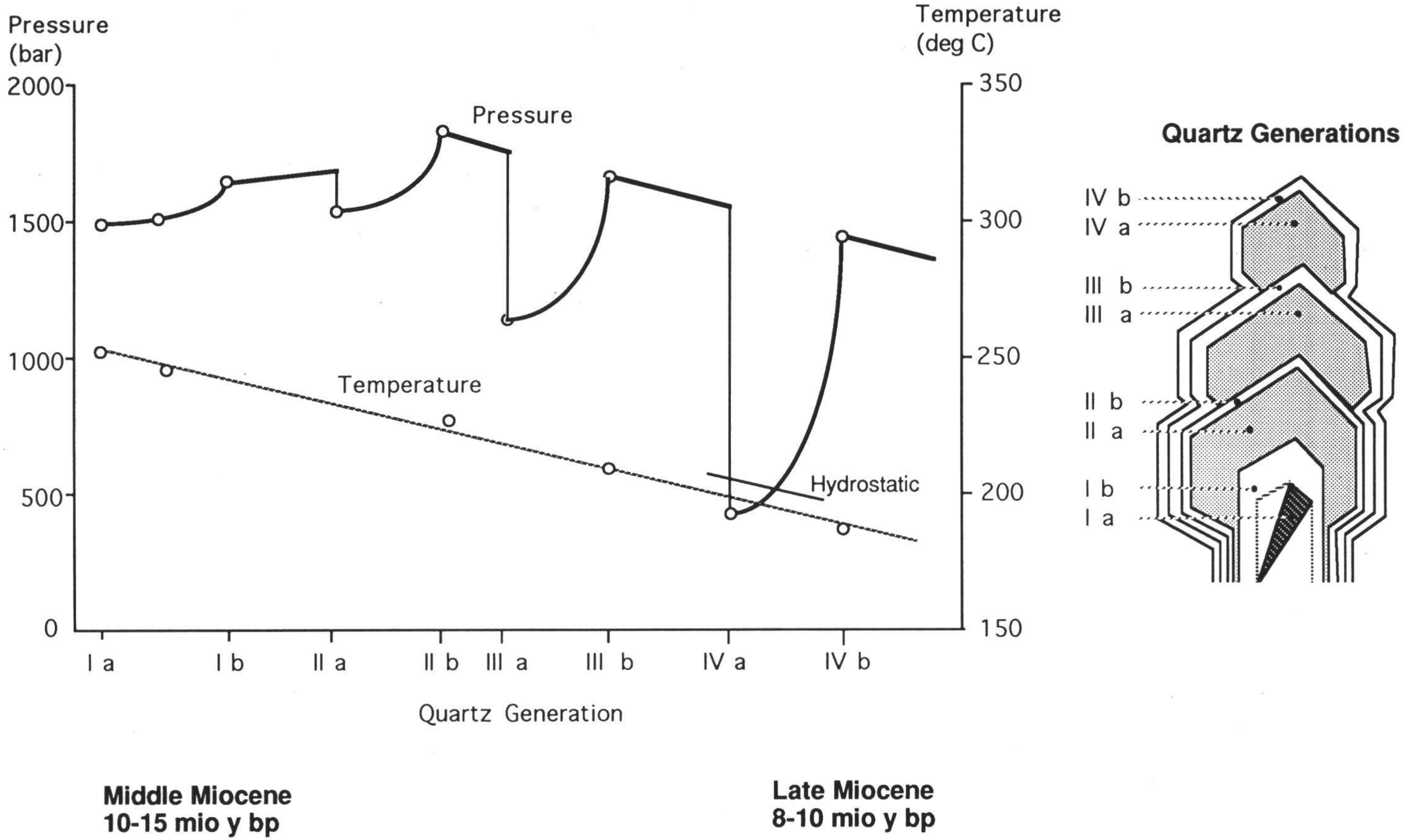

Fig. 3: Approximate pressure and temperature evolution of fluid trapping in quartz crystals, Val d' Illiez, northern Alps (Mullis 1976).

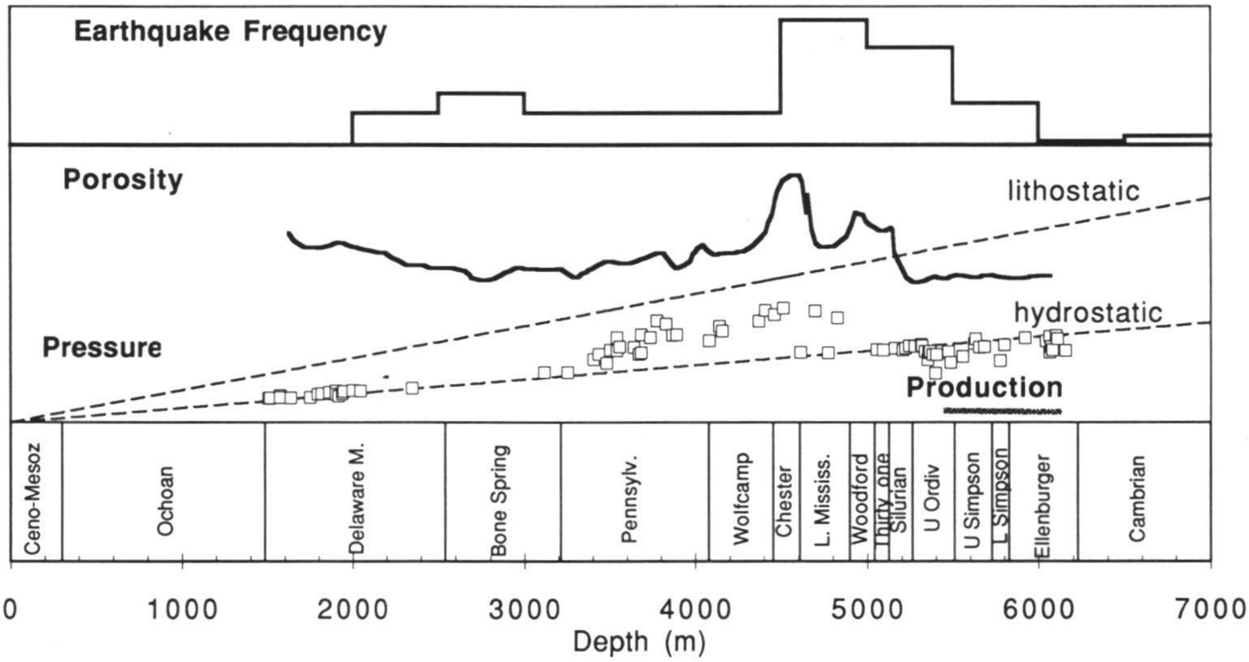

Fig. 4: Seismicity, porosity and pressure in the War-Wink field, Delaware basin, USA (Luo et al., 1994).

Also in the Gulf Coast, hydrocarbon generation and seismic valving are increasingly gaining acceptance as the major mechanism of overpressures and hydrocarbon migration, thus questioning older, but still widely accepted concepts of undercompaction and hydrocarbon expulsion (HUNT et al. 1994). Scattered seismicity is known to span over the area, both onshore and offshore.

Finally, the well known artificial seismicity induced by fluid injection through wells and reservoir impounding provides the most direct confirmation of the relationship between pore pressure and seismicity.

Fluid escape after fault rupture is accompanied by intense fracturing of the surrounding rocks, thus creating the necessary storage capacity to accumulate fluids after re-sealing of the escape fault due to plastic deformation and the precipitation of minerals after pressure and temperature drop. Trapping of these fluids is provided by the tight surrounding rocks which were not affected by connecting fractures (see Figure 1). The concepts of seismic valving, therefore, may unfold new opportunities in hydrocarbon exploration where conventional traps are absent or already exploited. The relationship between seismic valving and hydrocarbon accumulations is subject of another publication which is presently in preparation.

Apart from the above-cited sedimentary basins where seismic valving seems to be applicable, the proposed mechanism has good chances to be found elsewhere in the world (HUNT, 1990). According to TGK estimates, the majority of the known overpressured sedimentary basins (i.e. FERTL, 1976, HUNT, 1990) are seismically active.

Many highly productive wells in the Oklahoma region exploit isolated, fractured pressure compartments (i.e. Anadarko basin, see Al-SHAIEB, 1991, Arkoma basin), thought to be the result of seismic valving.

3. Overpressure prediction in the Alps of central Switzerland

TGK carried - out an extensive exploration programme for deep gas along the alpine front of central Switzerland (GUNZENHAUSER & BODMER, 1993). Hard overpressures are known from German and Austrian wells under comparable tectonic situations.
The extension of overpressures into the Swiss Alps, although not known from wells, is indicated by the following observations:

- The presence of distinct seismic velocity inversions below the Helvetic Nappes (Figure 5) suggests enhanced porosity, probably due to overpressure.

- The nature and distribution of surface gas indications and gas seepages suggest the presence of large regional seals which probably coincide with the base of the Helvetic nappes including some overthrusted slices of North - Helvetic Flysch: Hydrocarbon indications derived from direct observations and approximately 5000 soil gas measurements show that seepages at surface are abundant and diffuse near the edges and outside the nappes (high average soil gas concentrations), but scarce within the central part of the nappes (low average soil concentration, see Figure 6). Flow rates, however, are generally much higher inside the nappes and geochemically identified thermal gas from a major gas seepage can even be permanently inflamed at one location. Seepages within the nappes are predominantly concentrating along major fault zones.

- High hydrocarbon saturation in soils and in deeper formations (wells, tunnels and shafts) and isotopic and chemical composition point towards important active hydrocarbon generation in humic and sapropelic Permo-Carboniferous troughs.

- Low hydraulic conductivities (10^{-11} - 10^{-14} m/s), determined in Nagra boreholes at the Wellenberg site, penetrating into the base of the nappes, were observed and two of the three wells show a significant increase of formation pressure towards bottom - hole (KÜPFER, 1991, KAPPELER, 1994). Strong lateral and vertical pressure variations alternating between over- and underpressures are due to the presence of effective horizontal and vertical seals and pressure compartmentation.

Intense earthquake activity was recorded in the sediments below the Helvetic nappes, but practically none within the nappes or in the crystalline basement. Projection of the epicentres into the proper tectonic position (Figure 7) shows that seismicity is partially related to thrust planes as constructed from reflection seismic sections:

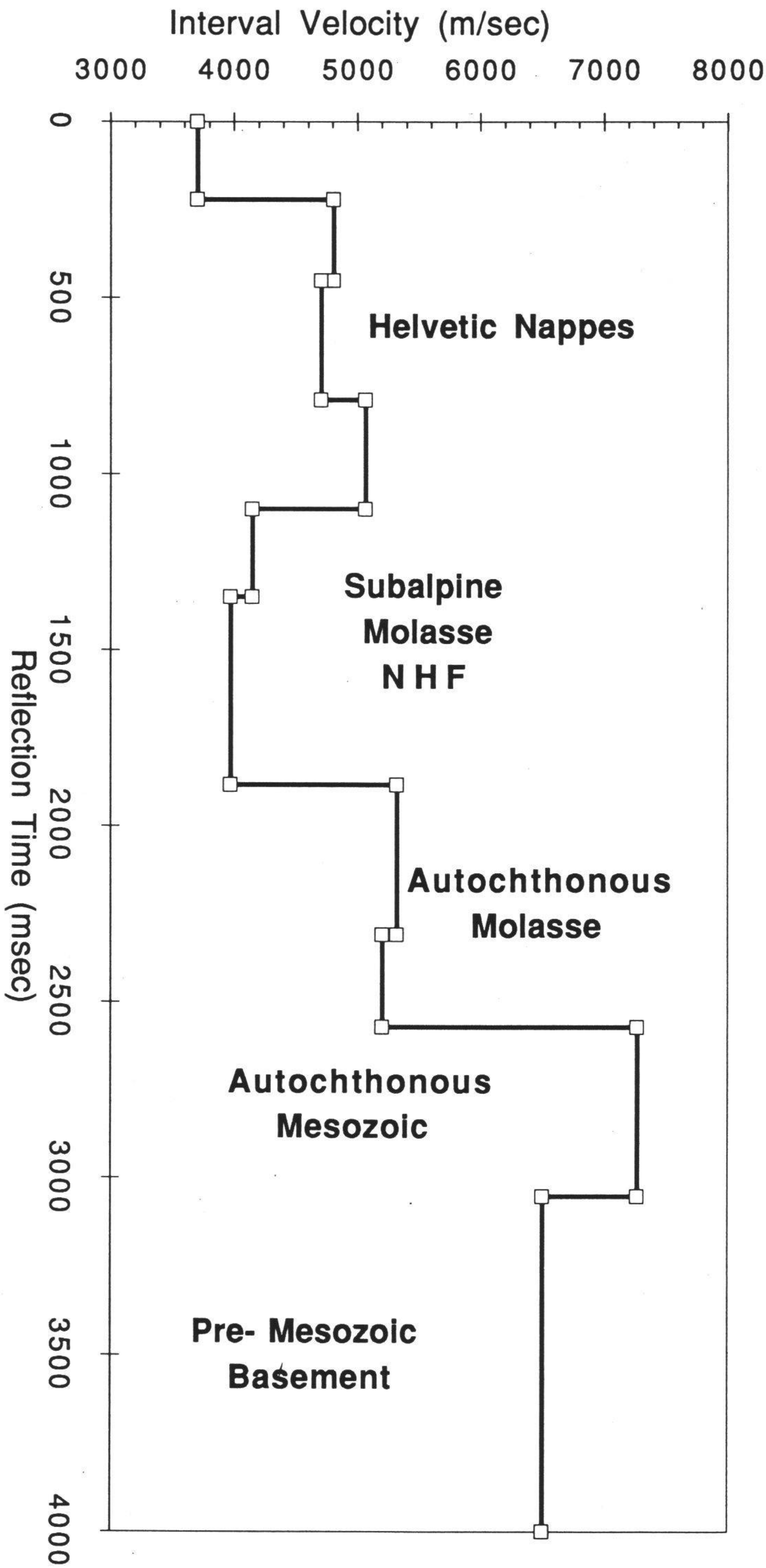

Fig. 5:
Typical seismic velocity distribution in the Alps of central Switzerland. Velocity inversion zones are commonly observed near the base of the Helvetic Nappes and, sometimes, near the basal overthrust of the Subalpine Molasse / North Helvetic Flysch (NHF) complex. Local anomalies indicating increased fracture porosity and permeability are observed in all sedimentary units below the nappes.

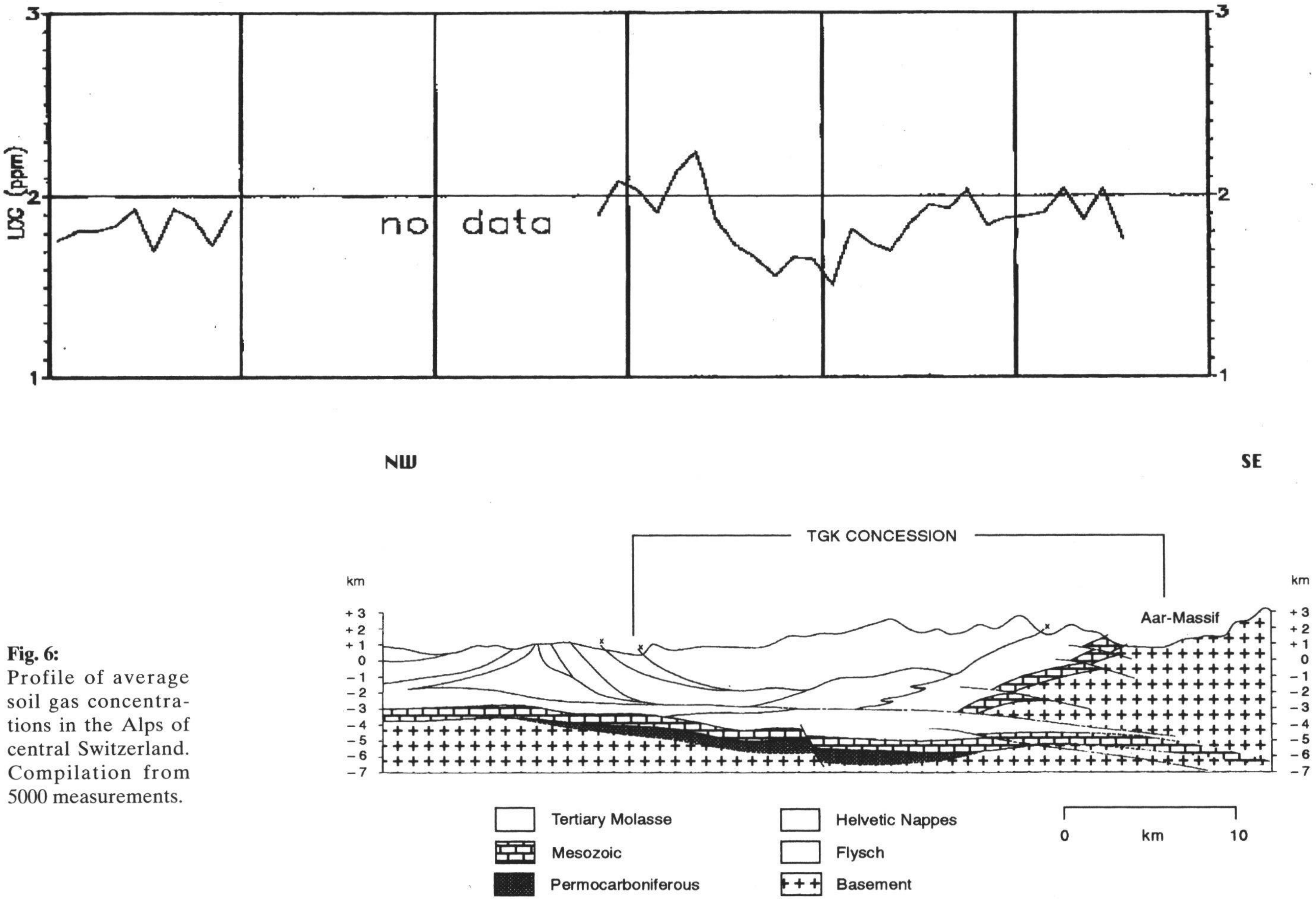

Fig. 6:
Profile of average soil gas concentrations in the Alps of central Switzerland. Compilation from 5000 measurements.

- the main overthrust of the Helvetic nappes ("Glarner Hauptüberschiebung"),
- the overthrust separating autochthonous Molasse and the Subalpine Molasse / North Helvetic Flysch (NHF) complex, and
- overthrusts between the imbricated thrust slices of the Aar Massif (BODMER & GUNZENHAUSER, 1992).

Numerous seismic events, probably connected to strike - slip movements, follow subvertical tectonic elements along the main valleys parallel to the profile illustrated in Figure 7. Seismicity following the Sarnen valley in the region Alpnach - Sarnen is remarkably concentrated in clusters. In this century, the majority of the earthquakes in this area were observed during the years 1917 and 1964 (more than 1000 events!) with little activity between or after the clusters. Clustering in time and in space, providing another strong argument for the importance of fluids and fluid pressure in earthquake mechanics, is commonly observed in many other areas in the country (DEICHMANN, 1992).

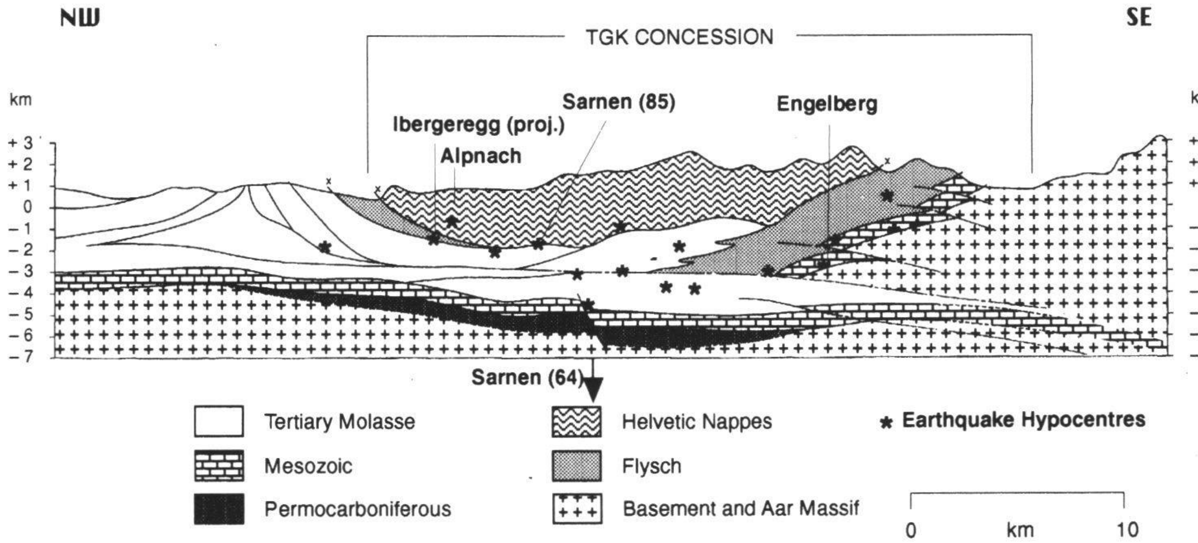

Fig. 7: Seismicity in the Alps of central Switzerland. Epicentres are laterally projected into the correct tectonic position. Focal solutions were determined for the labelled events (see Tables 1 and 2).

Assuming the validity of the seismic valving concept, seismicity is expected to concentrate in areas where horizontal permeability barriers impede the flow of fluids towards surface in order to allow for overpressure build-up. This relationship between low permeability and seismicity is documented by the well data near the base of the Helvetic Nappes as cited above. Application of the above formula published by SIBSON (1990) on reliable focal mechanisms (Table 1) confirm the presence of overpressures below the Helvetic Nappes and along the overthrust of Aar Massif slices ($0.39 <= \lambda_v <= 0.43$, see Table 2). Fault planes below the hydrocarbon generating, Permo-Carboniferous formations and within the nappes are favourably oriented and pressures causing fault rupture, therefore, are expected to be normal ($\lambda_v <= 0.34$).

location	year	event	coordinates		mag.	depth	P-axis		T-axis		geology	reference
		no.	X	Y		(km)	azi	dip	azi	dip		
Alpnach	85	711	666100	197000	2.5	1	285	22	70	64	Nappes	Deichmann&Pfister (1977)
Ibergeregg	89	447	702500	210400	2.5	3	281	48	58	33	NHF/Molasse	Deichmann&Pfister (1977)
Engelberg	89	614	674500	188500	2.9	5	151	13	54	29	Aar Massif	Deichmann&Pfister (1977)
Sarnen	85	953	666400	192300	2.9	8	307	71	211	2	Base Nappes	Deichmann&Pfister (1977)
Sarnen	64	2	665600	194500	5.0	11	139	11	37	44	Basement	Pavoni (1984)

Tab. 1: Selected focal mechanisms in central Switzerland (see also Figure 7). The location of the events (except event #2) was determined by raypath modelling and a crustal model derived from reflection seismic data (DEICHMANN & PFISTER, 1990).

location	year	$\delta\sigma 1$	E1	E2	$\mu 1$	$\Delta\sigma$	$\lambda 1$	$\lambda 2$	λ
Alpnach	85	331	24.03	30.35	0.75	2.0	0.34	0.35	0.34
Ibergeregg	89	330	19.22	17.29	0.75	2.0	0.39	0.42	0.39
Engelberg	89	333	36.21	51.84	0.75	2.0	0.43	0.94	0.43
Sarnen	85	332	8.76	34.78	0.75	2.0	0.65	0.40	0.40
Sarnen	64	331	28.58	61.42	0.75	2.0	0.34	1.42	0.34

Tab. 2: Overpressure computation using focal mechanism data. $\delta\sigma 1$ denotes the orientation of the maximum principal stress interpolated from the Seismotectonic Map of Switzerland (PAVONI & MAYER-ROSA, 1977), E1 and E2 define the angle between $\sigma 1$ and the alternative fault planes, the P and T - axes are defined by their azimuth (azi) and dip angle, $\mu 1$ is the coefficient of internal friction and $\Delta\sigma$ the difference between maximum and minimum principal stress. $\lambda 1$ and $\lambda 2$ are the pore pressure factors corresponding to the fault planes E1 and E2 as determined by the formula by SIBSON (1990), see text, and λ is the pore pressure factor at fault rupture (the minimum of $\lambda 1$ and $\lambda 2$).

The pressure predictions carried - out using seismological data are in line with the few existing well data, and other overpressure indicators derived from various geophysical and geochemical surveys. Earthquake - derived fault orientations partly coincide with some discontinuities visible on seismic sections. Other discontinuities such as the base of the Glarus nappe and other subhorizontal overthrusts would require lithostatic pressures to become re-activated (θ_r). Fluid inclusion data confirm that such elevated pressures were indeed existing in the vicinity of the base of the Helvetic Nappes (MULLIS et al. 1994) but have dissipated since Middle Miocene.

4. Conclusions

The TGK investigations in the Alps of central Switzerland lead to the conclusion that SIBSON'S seismic valving concepts are applicable to that area. The study of local seismicity in unexplored sedimentary basins along with a geochemical investigation of surface hydrocarbon indications and fluid inclusions in vein fillings may well be a promising new approach in hydrocarbon exploration. Overpressure prediction using focal mechanisms is proposed as a useful application in hydrocarbon exploration in areas, where no or little drilling information is available. Such preliminary information could be used either for the estimation of hydrocarbon - generating potential in unexplored sedimentary basins, but also to anticipate pressure problems connected to deep drilling in virgin formations.

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