Paleokarst in the Pekisko, west-central Alberta: its origin, recognition from horizontal and vertical well logs and impact on reservoir development

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ABSTRACT
The Mississippian Pekisko Formation has been exploited extensively in the Gilby-Wilson Creek-Minnehik area (T39-45, R2-5W5; *Fig. 1*), using a combination of vertical wells in porous, commonly dolomitized lithologies and horizontal drilling in tighter, undolomitized grainstones. The unit is dominated by crinoidal grainstones containing abundant ooids and coated grains, brachiopods and bryozoans, which were deposited as shoals in an inner shelf setting. Other primary lithologies in the region include muddy packstones (outer shelf) and fine-grained dolomudstones (probably deposited in a peritidal, lagoonal setting). With the exception of the muddy packstones, all these lithologies typically exhibit a clean Gamma Ray log signature, often less than 15 API.

Processes Of Karst Formation And Sediment Infill

Solution karst may occur in a number of settings. These including meteoric (predominantly via dissolved CO2 giving carbonic acid combined with oxidation of vegetation), deep burial (solution through hydrothermal activity or H2S producing sulphuric acid) and in mixing zones (mixing of fresh and marine water in coastal settings) (Ford 1988; Wright 1991). The effects discussed within the present study are all related to meteoric dissolution; based on the predominance of vertical or subvertical structures in the Pekisko this corresponds to the “early karst” phase of Choquette and James (1988). The kinds of structures formed during karsting rely on a number of variables, including climate, duration, vegetation and rock type among others (Budd et al. 1995). Of particular importance to Pekisko karst development are the original porosity-permeability characteristics of the rock and the variable climate from Mississippian through mid Cretaceous times.

Karst dissolution is most typically initiated by the subaerial exposure of carbonates and introduction of CaCO3 undersaturated meteoric waters (Kerans 1989). In poorly cemented carbonates (typically recently deposited), diffuse (interparticle) flow predominates with only minor utilization of fractures (White 1969; Choquette and James 1988; Kerans 1989), while in carbonates with low porosity and permeability, conduit (fracture) flow predominates. Resulting karst features where diffuse flow predominates include surface caliche deposits (formed by continual evaporation and recharge of water in highly porous soils and limestone) and limited cave formation reaching only several metres depth. Limestones with low porosity and permeability tend to develop little or no caliche, have abundant fracture-related conduits, and cave systems extending anywhere up to several hundred metres below the surface. In addition to these macroscopic features, porosity can also be developed on a microscopic scale through the leaching and dissolution of limestones (see Budd et al. 1995).

Meteoric macrokarst development in well-cemented carbonate settings begins with dissolution of fractures into a series of grooves and flutes; Bocker (1969) suggested that fractures only 10μm wide are needed for dissolution processes to begin via laminar flow. Once these have widened to between 5 and 15 mm, turbulent flow occurs, speeding up the dissolution process via more active dissolution and mechanical abrasion; it is this lower limit that Ford (1988) defines as marking initial cave formation. At this point, vertical, subvertical and horizontal cave systems develop within the vadose and upper phreatic zone, with cavities being enlarged by collapse and brecciation of cave roofs and dolines (sinkholes). The vadose zone (above the mean water table) is dominated by vertical and subvertical structures with occasional "canyon-like" caves, while the more typical caves characterized by a circular or ovoid cross section develop in the upper phreatic zone at the level of the water table. As karst development continues through time, the vadose zone becomes progressively deeper through solution,

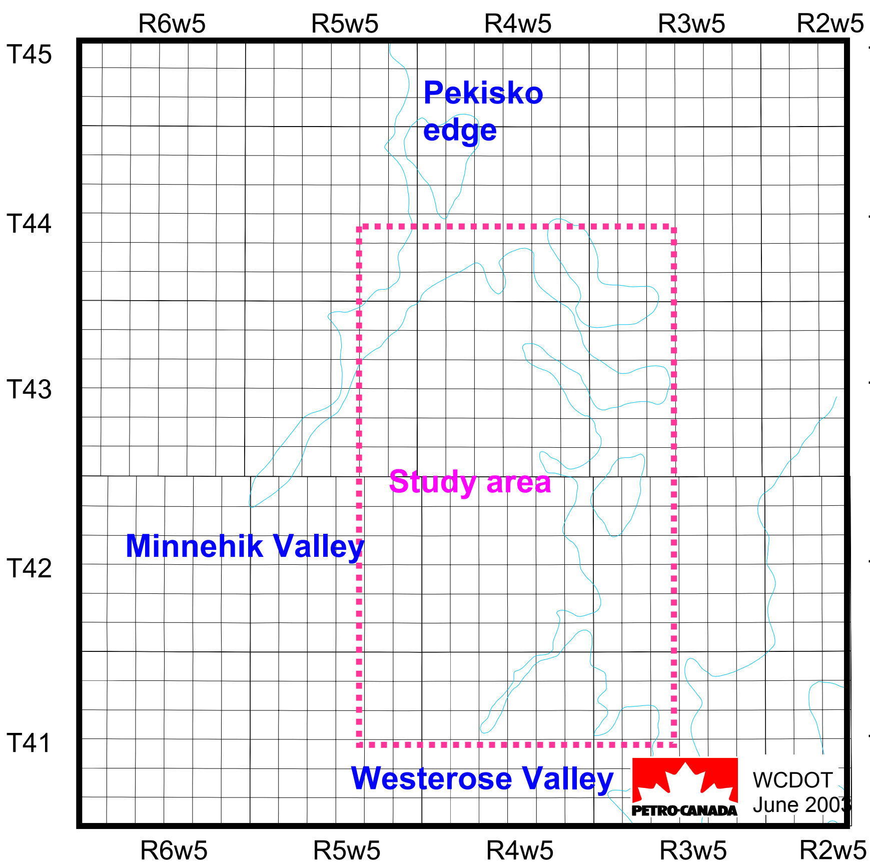

Fig. 1. Study area showing location of Pekisko edge and main Cretaceous incised valleys.

resulting in a downwards movement of the water table or during lowering of sea level; both result in overprinting of early phreatic features by later vadose karst.

Sediment deposition can occur both during cave formation and following a change in base level (such as sea level rise). In the former case, deposits include speleothem (limestone deposits such as stalagtites and other dripstones), cave floor breccias formed by roof collapse, and fine-grained clastic material being transported from the surface by flowing water (Ford 1988; Loucks and Handford 1992). Clastic material is dominated by finely laminated green, grey and black muds and silts which are commonly laminated parallel to the karst surface (whether horizontal or vertical). Higher energy flow may lead to the introduction of coarser material such as fine sand and silt; these can exhibit a variety of sedimentary structures more commonly associated with surface flow such as cross-bedding and grading. During transgression, an open cave system may be entirely filled with marine sediments which may be either clastic or carbonate dominated; infilling may also occur through surface fluvial processes.

Paleokarst refers to karst features formed in a geologically earlier time. Wright (1991) divided these into: Relict paleokarst (surface karst in geologically recent rocks which developed under different climatic conditions than in which it is now found, relating mostly to Cenozoic karst); Buried paleokarst (where karst took place prior to burial by younger sediments); and Exhumed paleokarst (pre-existing paleokarst which is now being exhumed and exposed to further karstification). Polyphase karsting (related to the last two of these) is relatively common and is probably what occurred in the Pekisko of west-central Alberta.

Recognition And Timing Of Paleokarst Development In The Pekisko

Evidence of paleokarst in the Pekisko is seen in cores (*Fig. 2*), drill cuttings, high Gamma Ray (GR) log spikes, low Photoelectric Factor (PEF) readings and anomalously high porosities on limestone-scale Neutron-Density (N-D) logs, and rotated blocks on Formation Micro-imager (FMI) logs (*Figs. 3-5*). The occurrence of drill-string drops during drilling and cavities shown on caliper logs, as have been used to detect the presence of open caverns in some other karsted reservoirs (e.g., Dembicki and Machel 1996), cannot be used in the Pekisko as most caves appear to be fully sediment-infilled. During the drilling of horizontal wells, paleokarst features are visible on MWD GR logs through elevated GR>45 API, commonly associated with spiked gas detector readings of 2000 units or more. These may be distinguished from open fractures which have low GR readings and a long “tail” on the gas spike.

In addition to erosion at the upper and lower contacts of the Pekisko, paleokarst features are developed as: 1) Vertical, inclined and horizontal green-shale filled fractures < 1cm wide; 2) Sand-filled sink holes 1-5 m wide; 3) Fractures and cave eposits with collapse breccias and laminated green and black shale matrices varying from 1cm to several metres extent. Karst infill features visible in core appear to be very similar to those described from the Lower Ordovician Ellenburger Group of West Texas (Kerans 1990), a carbonate sequence with similar lithologies to the Pekisko and over 3 billion BOE reserves.

Evidence of karst development is most common in wells which have been drilled in areas where the Pekisko is subcropping directly beneath the Middle Cretaceous Ostracod and Ellerslie formations, particularly within Cretaceous incised valley systems (see locations of Minnehik and Westerose Valleys on Fig. 1; also Reid 1998). It is, however, also present in wells where there are several tens of metres of overlying Jurassic strata (Nordegg, Poker Chip and Rock Creek) separating the Pekisko from the Cretaceous.

This suggests that there may have been multiple karsting events; the first would have been during Pennsylvanian to earliest Jurassic times. This would have been the event of longest duration (some 120 My) during which the later Mississippian Shunda was removed (assuming it to have originally been present over the entire region). There is no record of Permian or Triassic sediments in the study area; these may either have been removed or never deposited.

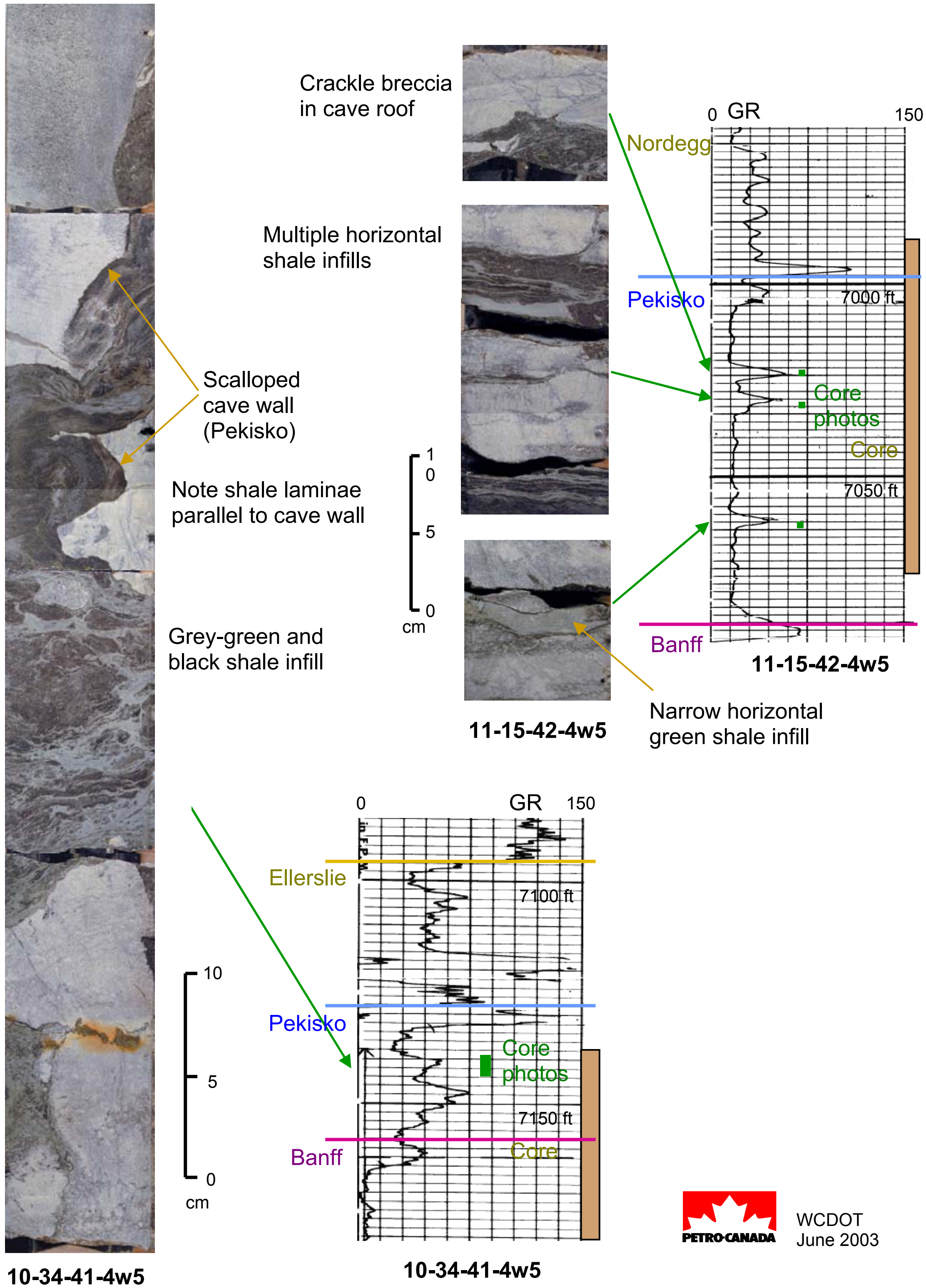

Fig. 2. Shale infilled paleokarst caves and fractures in Pekisko cores

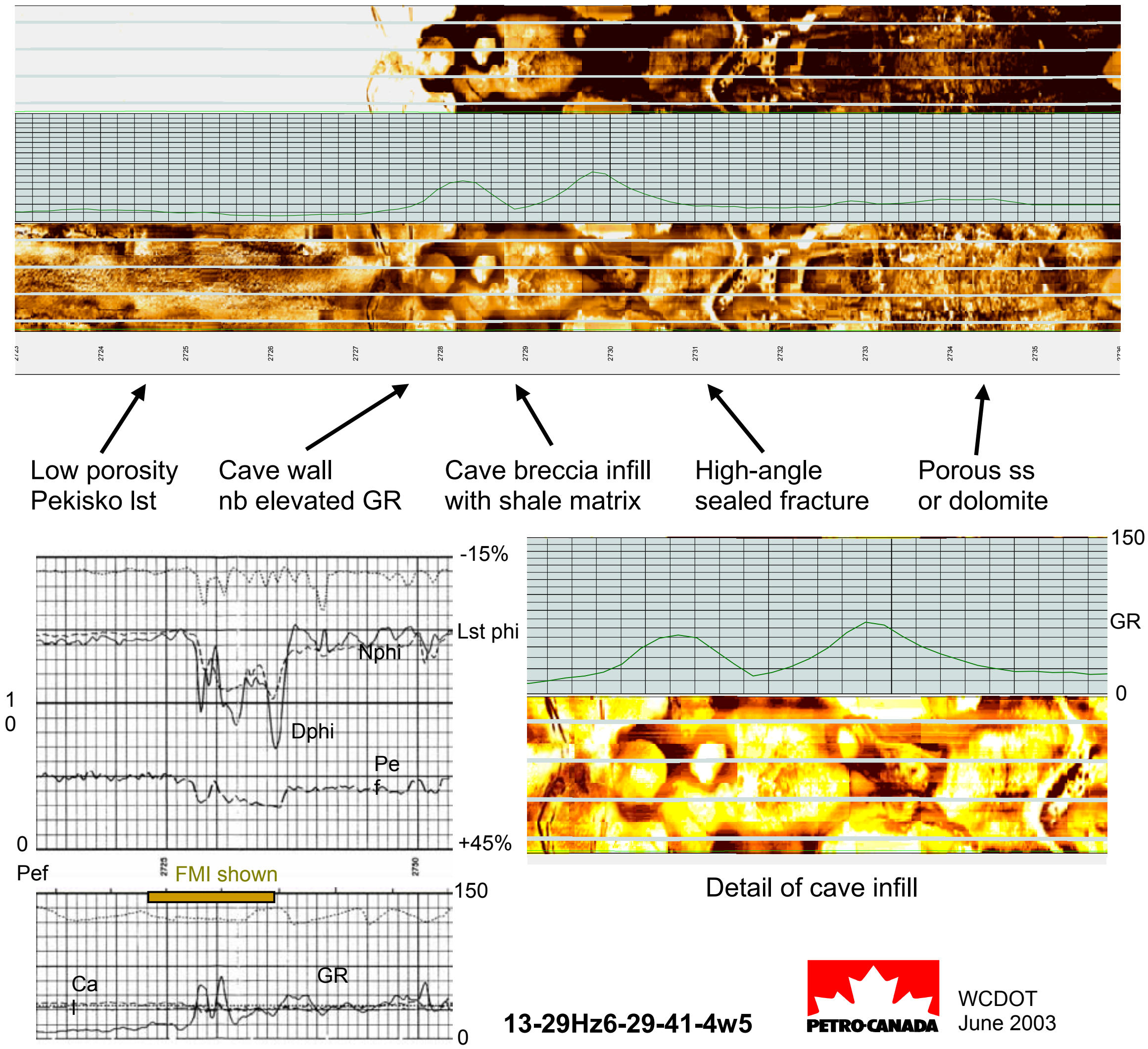

Fig. 3. FMI and N-D logs showing vertical shale-infilled collapse breccia in a horizontal Pekisko wellbore.

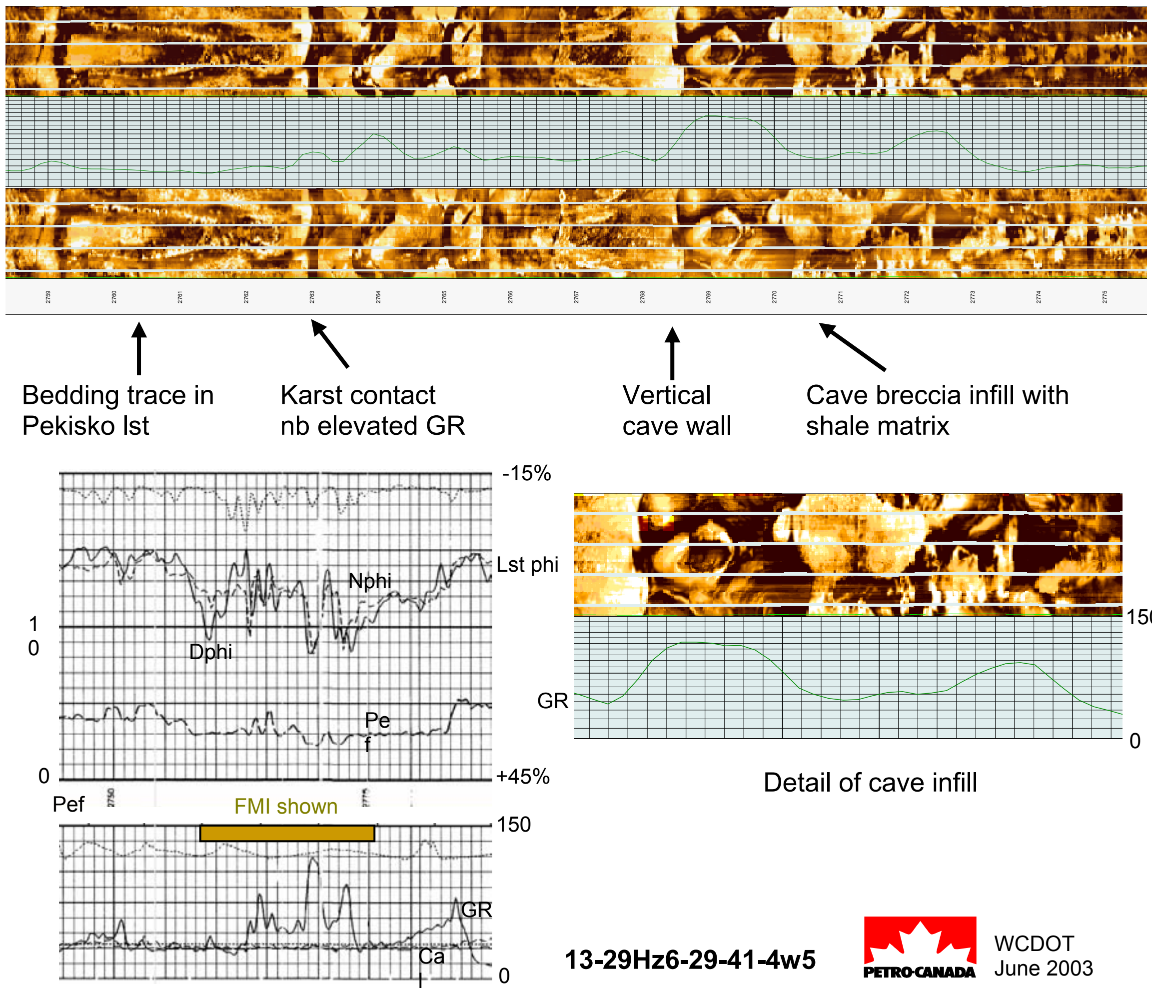

Fig. 4. FMI and N-D logs showing vertical shale-infilled collapse breccia in a horizontal Pekisko wellbore.

Pennsylvanian-age karsting of Mississippian carbonates has been documented widely from the North American craton (Meyers 1988; Sando 1988; De Voto 1988; Palmer and Palmer 1989; Esteban 1991; Demiralin et al 1993; Dixon and Saller 1995), where it led to the formation of economic hydrocarbon and MVT mineral deposits (e.g., Madison Limestone of Wyoming and Boone Formation of Missouri, Oklahoma and Kansas). The Pennsylvanian of the low-latitude North American Midcontinent was characterized by a relatively warm, humid climate (Walker et al. 1991), which would have promoted rapid and deep karst development. Evidence for Permian and Triassic karsting is less common, and the climate would have been relatively arid; documented Permian karst with hydrocarbon reserves (e.g., the Yates Field of West Texas) appears to have been related to marginal marine mixing zones (Craig 1988; Tinker et al. 1995).

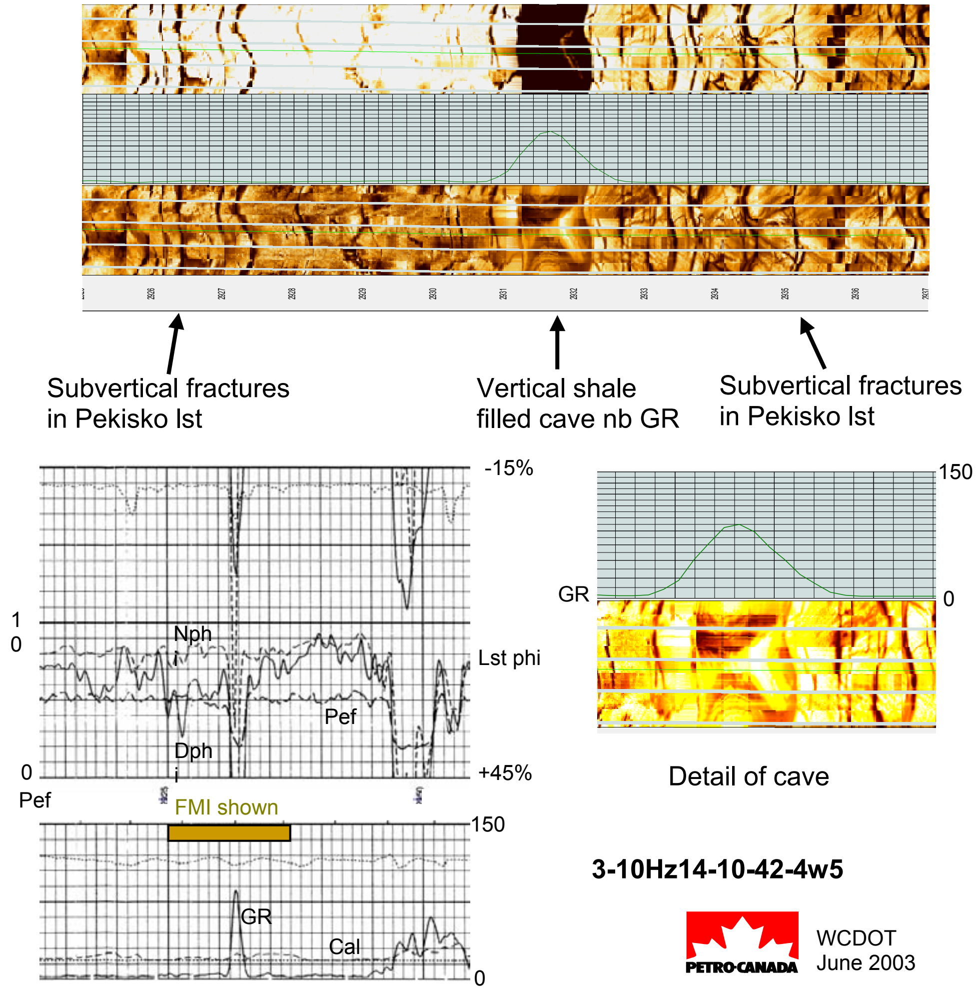

Fig. 5. FMI and N-D logs showing vertical shale-infilled cave in a horizontal Pekisko wellbore.

By early Nordegg times, the Pekisko had probably been eroded from the east of the study area, shown by local onlap of Nordegg directly onto the earlier Mississippian Banff Formation along the present Pekisko edge. Although the basal Nordegg essentially rests on a peneplaned surface, there is local (apparently fault-controlled) relief and at least one well appears to have drilled through a (?early Jurassic) pre-Nordegg valley-fill. Thus, it is here assumed that at least some of the karst features observed in the Pekisko were formed in this Pennsylvanian to early Jurassic interval. It is, however, most likely that the majority of the features are late Jurassic to early Cretaceous in age. The reason for this is that the most spectacular and extensive karsting recognized in core and in vertical and horizontal well logs occurs along Cretaceous incised valley floors where the Pekisko directly underlies Ellerslie and Ostracod sands and shales of Middle Cretaceous (Albian) age. Although marking a shorter interval of exposure (maximum 60 My), this period of geological time was characterized in western Canada by tectonic uplift and a warm, moist climate, both of which probably contributed to elevated rates of karst formation. An attempt to date some of the karst infill sediments is currently ongoing in order to determine the timing of maximum karst development.

Impact Of Paleokarst On Pekisko Reservoir Development And Production

Paleokarst macro-features in the Pekisko appear to commonly run subparallel along fracture zones, the presence and orientation of which may sometimes be deduced prior to drilling through subsurface mapping. The majority of fractures in the Wilson Creek area are related to a conjugate fault set oriented ENE and SSW. During the drilling of horizontal wells over the past six years, it has become evident that open fractures often lead to the most productive wells. Unfortunately, when the fractures are shale-filled they vertically partition the reservoir and can lead to reduced recovery in horizontal wells. Given that shale-filled paleokarst features are more common where Cretaceous sediments rest directly on the Pekisko, horizontal wells are more likely to be successful if drilled in areas where the Pekisko is overlain by at least a partially complete Jurassic sequence.

In terms of orientation, it would be expected that horizontal wells with azimuths which cross the regional fracture trends should have better production rates than those which run parallel to them. It appears, however, that other variables in terms of local porosity development tend to blur analysis of this trend. Furthermore, if these fractures are infilled it will reduce, rather than enhance, production.

Finally, in this area it appears that matrix porosity generally decreases towards the Pekisko edge, in addition to an increase in macroscopic paleokarst features. It is unclear whether this represents a late-stage blocking of earlier porosity, or whether porosity downdip from the edge represents enhancement of the earlier porosity. This suggests that wells are more likely to be successful if drilled several kilometers downdip away from the Pekisko edge. This is contrary to the conclusions of Reid (1998), who considered the formation of Pekisko microporosity in the Twining oil field (T30-33, R 23-25w4) to have been related to karst dissolution along the Pekisko edge. The complex variables controlling microscopic porosity enhancement versus porosity blocking during karsting is a complex subject (see Budd et al. 1995, Matsuda et al. 1995, Wagner et al. 1995 and Dixon et al. 1995), which is beyond the scope of the present paper.

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