AAPG HEDBERG CONFERENCE
"Deformation History, Fluid Flow Reconstruction and Reservoir Appraisal in Foreland Fold and Thrust Belts"
May 14-18, 2002, Palermo – Mondello (Sicily, Italy)

Tectonic and Thermal forward modelling of Canadian Foothills An essential approach for reservoir appraisal, fluid flow and pore pressure history

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Introduction

Defining a structural scenario that describes the evolution of the foothills requires knowledge of the temporal relationships among deformation, fluid flow and diagenesis. This allows the pore fluid pressure history in subthrust reservoirs to be quantitatively analyzed. The structural scenario can be derived from regional geological data, that fits: (1) Present maturity data, computed from the transformation ratio (Ungerer et al., 1990); (2) apatite fission track data after the computation of the thermal regime at each stage of the scenario; and (3) the present day temperature data. This modeling is performed in a forward mode with complementary 1D (GENEX software; Forbes et al., 1991 and Espitalié et al., 1985) and 2D models (THRUSTPACK, Roure & Sassi, 1995).
In the second modeling step, 2D templates computed with THRUSTPACK for successive intermediate geometries are uncompacted (backstripped) in a backward mode with the CERES software, and then used to model fluid flow and pore pressure history (Schneider et al., this session). The burial and thermal history obtained for individual reservoir horizons is also compared to diagenetic observations (microtermometry of fluid inclusions, stable isotopes …), indicating absolute ages of the different diagenetic processes accompanying thrust propagation.
We shall describe in detail the methodology developed to obtain such a geological scenario, thermal history and maturity evolution in a tectonicaly complex area, the Rocky Mountains Foothills in Alberta along the Calgary-Banff cross-section drawn by Price and Fermor in 1982.

Tectonic style and agenda of thrusting

The fold- and thrust- belt of the southern Canadian Cordillera is characterized by thin-skinned tectonics (Bally, 1966). All the faults merge at depth into a common sole thrust in Cambrian formations, just above the Precambrian crystalline basement. The geometry of the thrust faults is a succession of flat segments linked by steeper ramps. However other secondary detachment levels exist. Numerous shaley levels have been identified as potential decollement horizons, the most important of which are located within Bearpaw shale (Upper Cretaceous) which accounts for the passive roof thrust of a triangle zone that develops at the front of the foothills.
During the Upper Jurassic an early foredeep basin developed in relation to the onset of the Colombian Orogeny west of the Purcell Thrust (Omineca Belt; Price, 1973; Poulton et al., 1994). The Purcell Thrust is currently located in the vicinity of the former thrust front of the Cordillera. This thrust is effectively cut by post-kinematic granitic plutons, which were dated at 122 to 94 Ma by Hoy and Van der Heyden (1988).

In contrast, the onset of the main Laramide compressive phase is dated in the inner part of the Cordillera at about 85-80 Ma. Therefore, we have decided to initiate the tectonic contraction along the Fatigue-Simpson Thrust, situated in a more external part, slightly before 80 Ma (fig.1). Farther east, thrusts were assumed to move in a regular sequence with a constant velocity, until they reached the first target age, which is coeval with displacement on the McConnell thrust. By a trial and error process, we increased progressively the amount of displacement along individual thrusts until we could fit both the age and geometry of the target. The onset of displacement on the McConnell Thrust has been dated by Covey et al. (1994) at 77 Ma, but its major motion was most certainly finished at 65 Ma. Farther east, other thrusts were activated later, and these moved in sequence with a constant velocity until they reach the second target age at the end of the Laramide Orogeny, which is estimated at 55 Ma (Price, 2000). Between 55 to 20 Ma important regional erosion affected the whole cross-section.

Methodology

Initial processing of the data is necessary to:

- 1) Define the initial architecture of sedimentary strata and thrust faults. We have used IFP's LOCACE software to restore the section in its pre-orogenic configuration, starting from the present day architecture of the balanced cross-section. We have decided to start the modeling at the onset of the deposition of the Cadomin Formation (115 ma), i.e. at the top of the Kootenay Formation, after the deposition of the first synflexural sedimentary wedge. The great majority of structural units have been restored by a flexural slip method with the LOCACE software. The geometry of individual thrusts and folds is very complex in the Cretaceous formations of the foothills. THRUSTPACK could hardly manage such a large number of independent modules. Therefore, before the modeling, we simplified the overall geometry of the cross-section by reducing the number of thrust faults within the shallower horizons. We ascertained that this simplified cross-section was indeed reasonably balanced (trial and error).

- 2) Constrain the different sedimentary and topographic profiles through time, for the entire section (i.e. for the foreland part as well as for the foothills and the hinterland). This implies we must estimate the former thickness of eroded layers. For this purpose, we have used both the LOCACE software, which provides results based on geometrical considerations, and the GENEX software, which provides independent estimates based on 1D thermal modeling.

We have first restored the initial sedimentary pile of the Cretaceous thrust sheets, by flattening the base of these layers. Then, it was possible to draw the mean position of the various layer interfaces. By successively removing each individual horizon, we could obtain the thickness of compacted formations at places where they have not been totally eroded. In contrast, for the Paskapoo Formation in the foothills and for all the Cretaceous formations in the Front Ranges, which are now totally eroded, we have computed the total eroded thickness by 1D thermal maturation modeling with GENEX© software (see below).

In the Interior Plains the amount of erosion of Paleocene-Eocene continental sediments increases progressively from 1800 m in the east up to 3800 m, just in front of the foothills. In the foothills, the eroded thickness of Upper Cretaceous-Lower Tertiary ranges from 3300 to 4600 meters, whereas in the Front Ranges there is up to 8000 meters of Cretaceous strata. In the latter area however, it is possible to argue that Tertiary formations were never deposited.

- 3) Specify the timing of each individual thrust fault motion. Due to the complete erosion of synkinematic layers in the Front Ranges of the Rocky Mountains, it was necessary to perform this analysis at a regional scale, using the distribution of synorogenic sedimentary strata in both the allochthon and the foreland, and to use the cross-cutting relationships among major thrust systems. This was a key procedure to determine which formations were initially deposited on each individual thrust sheet.

The basic assumption made for managing thrust initiation during this study was a forward thrusting sequence that propagates from the hinterland toward the foreland. For each deformation stage, the topography was reconstructed using the critical tape theory developed for inland and offshore accretionary wedges (cohesive Coulomb theory; Davis and al., 1983; Dahlen and Suppe, 1984). In this theory the mean topography or overall geometry of a tectonic wedge results from a constant balance between the amount of shortening, pore fluid pressure, mean dip of the basal decollement level and amount of erosion.

Results of 1D and 2D subsidence, thermal and kinematic modeling

1) Tectonic subsidence curves show a rapid acceleration at Mississippi and Devonian times, either in relation to the Antler Orogeny (compressional event), or due to intracratonic crustal thinning (thermal/extensional event). They show also a very rapid acceleration and a longer-term evolution of subsidence during Upper Cretaceous to Paleocene times, in response to the orogenic tectonic loading. Finally, subsidence curves also show a synkinematic uplift episode due to tectonic accretion and foreland propagation of the thrusting, as well as a subsequent and important episode of regional, post-orogenic uplift, developing between 55 and 20 Ma.

2) The basement heat flow used to obtain a good fit in 1D and 2D with the present day temperature distribution is around 40 mW/m2 at the top of the basement. This is similar to the heat flow computed with the present day temperatures in other studies in this region (Bachu and Burwash, 1994). We decided to keep this basal heat flow constant during all of the compressional history of the Alberta flexural basin. Indeed, no important geodynamic event responsible for drastic changes in thermal boundary conditions has ever affected the region since Devonian/Mississipian time (Antler Phase) until the Eocene. However, the resulting temperature profiles account for a blanketing effect that developed during the formation of the flexural basin, synchronous with tectonic loading.

3) The thermal modeling outlines lateral variations from 120 to 240°C for peak temperatures reached by the principal carbonates reservoirs (Mississippian) during sedimentary/tectonic burial, due to synflexural sedimentary wedge and thrusting. This increase of the maximum temperature is progressive towards the internal part of the belt. However it is not linear and the maximum temperature is reached at different times in the hinterland, foothills and foreland (fig.2). Indeed the maximum temperature results from a balance between competing factors, i.e. the maximum burial due to sedimentation and thrust loading, and tectonic uplift and coeval erosional unroofing of the reservoirs.

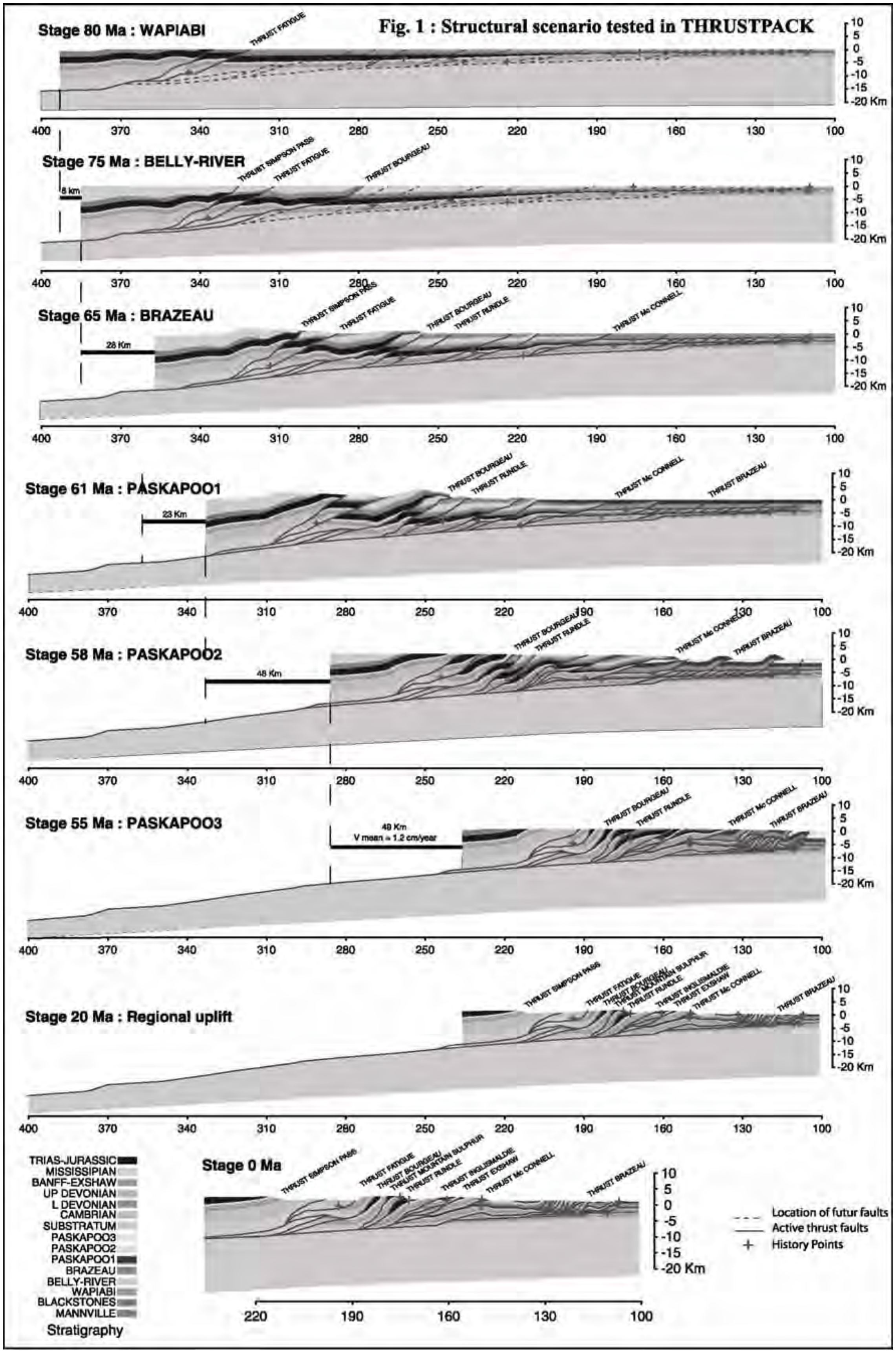

Fig. 1 : Structural scenario tested in THRUSTPACK

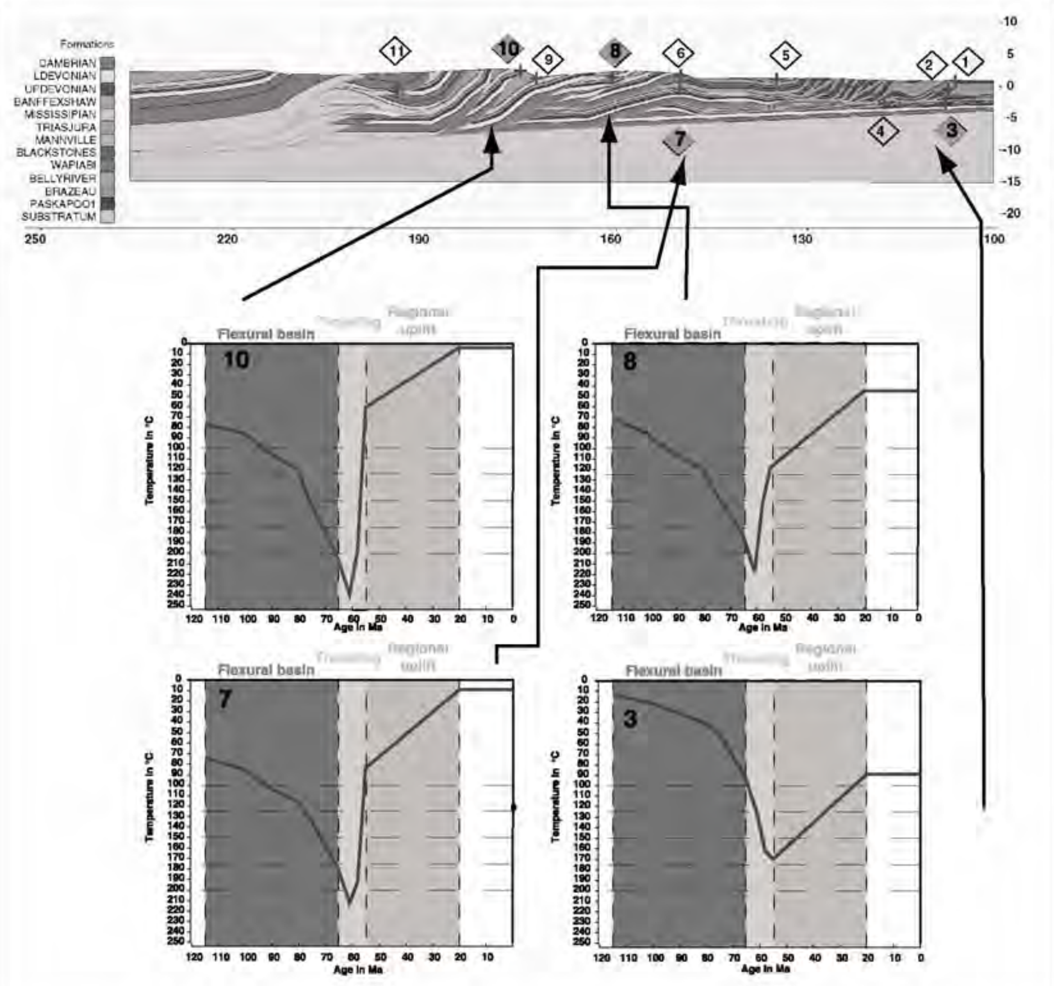

Fig. 2: Temperatures versus time curves computed by THRUSTPACK

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