

**Confirmation of Thin-skinned Thrust Faulting in Foreland Fold-Thrust Belts and
Its Impact on Hydrocarbon Exploration:
Bally, Gordy, and Stewart, Bulletin of Canadian Petroleum Geology, 1966***

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Low-angle thrust faults were first recognized in 1841 by Arnold Escher von der Linth in the Alps near Glarus, Switzerland (Bailey, 1935), and by James M. Safford (1856) in Tennessee, and later by A.E. Törnebohm (1872) in Sweden and R.G. McConnell (1887) in the Canadian Rockies, but their very existence became a point of contention. This prompted the Director of Her Majesty's Geological Survey, Roderick Impey Murchison, to dispatch his best geologists to the Northwest Highlands of Scotland where an excellent candidate for such a structure was thought to exist. They were instructed to once-and-for-all to disprove the heresy that thin sheets of rock could be transported intact for many tens of kilometers. B.N. Peach, John Horne, C.T. Clough, and their colleagues mapped the Assynt District in enough detail to thoroughly confirm the existence of the Moine thrust (Peach et al., 1892, 1907), so British geologists could agree with their Alpine and Appalachian colleagues. Peach et al. (1907), however, only laid the foundations for other controversies that followed. At the same time and later, Swiss geologist Arnold Buxtorf (1907, 1916), based on geologic data from construction of railroad tunnels, published the idea that the faults and folds in the Jura Mountains are rootless and formed by propagation of a detachment through Triassic evaporates, leaving the basement beneath undeformed—the first statement of thin-skinned thrusting and folding (Laubscher, 1962; Rodgers, 1964). The argument about thin- vs. thick-skinned thrust faulting in foreland fold-thrust belts thus began in the early 1900s and raged for many decades, although the solution was at hand on the Earth's surface in the late 19th and early 20th centuries. Cross-section construction was aided by development of the concept of down-plunge projection by Emile Argand (1916) and later by J. Hoover Mackin (1950), but subsurface data are essential to construction and confirmation of valid cross sections. Confirming evidence from subsurface data from a combination of drilling and high quality seismic reflection lines would not become available until the 1950s.

Actually, C. Willard Hayes (1891) recognized the low-angle character of the thrust faults in northwest Georgia, probably thought they are thin-skinned, and even speculated on how a cross section through these faults might be retrodeformed to estimate shortening. John L. Rich rode in an airplane over the Pine Mountain fault block in the southern Appalachians in the early 1930s and became intrigued by its structure. He subsequently published a paper in the *AAPG Bulletin* clearly showing the Pine Mountain block is thin-skinned (Rich, 1934), but without any supporting subsurface data. Modern seismic reflection data have confirmed Rich's speculation, as well as the largely correct nature of his cross sections illustrating the Pine Mountain structure as a modern “fault-bend fold,” and his conclusions about the displacement, character, and behavior of bounding tear faults (Mitra, 1988). The thin- vs. thick-skinned argument, however, raged in the Appalachians throughout the 1950s and early 1960s between two protagonists, John Rodgers and Byron M. Cooper (Rodgers, 1949, 1964; Cooper, 1961

1964), but neither gave an inch, because there were no subsurface data in the Appalachians to support either side. Drilling data, however, did provide sufficient information to dispel any doubts about the thin-skinned character of deformation in the Appalachian Plateau (Gwinn, 1964).

The interior Appalachian foreland fold-thrust belt (Valley and Ridge) was considered overmature and largely barren of hydrocarbons, but the Canadian Rockies Foothills were becoming quite productive during the 1950s and 1960s, with Turner Valley field having already been productive for several decades (Tippett et al., 2005). Subsurface drilling data were already quite abundant and the first digital seismic reflection lines through this area were being acquired by several companies. Shell Canada geologists Albert W. Bally and Peter A. Gordy, and geophysicist Gordie A. Stewart, were allowed to publish the results of their analysis of numerous seismic reflection profiles in their 1966 *Bulletin of Canadian Petroleum Geology* paper, "Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains." Their management permitted them to acquire long regional seismic profiles across the Canadian Rockies and Foothills yielding seismic images that clearly showed the undeformed basement dipping gently westward beneath the foreland fold-thrust belt. These thus became the critical data to declare thin-skinned thrusting to be the mechanism for deformation of thrust belts worldwide. So, while the thin- versus thick-skinned thrusting concepts had been fiercely debated in the Appalachians and elsewhere, the debate was silenced with interpretation of a few critical high quality seismic reflection profiles in the Canadian Rockies and Foothills, calibrated by numerous industry wells. A key to the interpretation of the Shell Canada regional transects was the then newly developed "variable-area" displays, which for the first time permitted geologists to become more deeply involved in the interpretation of seismic reflection data. Moreover, the contrast of high-velocity carbonates and lower velocity foredeep clastics encouraged the use of in-line and broadside refraction techniques to identify "top carbonate reflectors" among a maze of flat and steep reflectors (for an overview see Keating, 1966). Thus the real "driver" for new geological insights was the aggressive application of then novel geophysical technologies: the confirmation of old geological concepts and their "morphing" into new geological insights came mostly as a consequence of technology and not as a consequence of the testing of a new geological hypothesis. This also was more a community effort and not the work of one company, despite the outlet through the Shell geologists (A.W. Bally, written commun., 2006). Another important element brought to the forefront in their paper was the importance of constructing rigorous cross sections that could be retrodeformed and deformed again to produce a believable result—section balancing. Others had previously discussed this (e.g., Hayes, 1891; Chamberlain, 1910; Bucher, 1933), but the recognition of a gently westward-dipping, "near-basement" Cambrian reflector in the Canadian Rockies for the first time permitted and called for the construction of balanced cross sections, and for regional strike profiles that respected surface geology, regional seismic reflection data, and drilling information. Implicit in the development of balancing techniques was the recognition that, particularly in the inner parts of the Canadian Rockies, the actual depth and thus the "tilt" of the basement, became increasingly uncertain. The addition of stratigraphic thickness uncertainties translated into widely varying shortening estimates. All of the original balanced sections were balanced by hand and at a scale that was good enough for exploration.

Hans P. Laubscher (1962) quantitatively addressed the concept of area balancing and other problems inherent with restoring cross sections, and, shortly after the Bally et al. (1966) paper, Chevron geologist Clinton D. A. Dalstrom (1970) published his classic paper summarizing the basic concepts of section balancing. Steven E. Boyer and David Elliott (1982) provided additional details about the nature of thrust systems, while Price and Mountjoy (1970), Elliott and Johnson (1980), Price (1981), and Elliott (1983) provided abundant evidence for the utility of balanced cross sections.

A hydrocarbon-bearing component of many foreland fold-thrust belts, which was confirmed and better

studied with the aid of multi-channel seismic reflection data, is “triangle zones.” The one in the Alberta Foothills was well documented during the 1970s and 1980s, where the most complex of these structures exists (Canadian Society of Petroleum Geologists Special Issue, 1996). Couzens and Wiltschko (1996), however, suggested there are at least two end-member types: the Alberta Foothills type that involves massive delamination within the sedimentary section and *retrocharriage*, producing as much as 50 percent shortening, and the simpler Appalachian type that forms with two oppositely vergent thrusts that involve detachment with minimal shortening in the cores of anticlines (e.g., Gwinn, 1964).

The Bally et al. (1966) paper should have convinced any remaining skeptics about the thin-skinned nature of foreland thrust faulting and provided a rationale for the construction of balanced cross sections. It therefore provided a new paradigm that changed the thinking about hydrocarbon exploration in thrust-faulted regions worldwide. While the understanding the structure of foreland fold-thrust belts is still incomplete, A. W. Bally (written commun., 2006) senses that today’s styling of regional structure across foreland fold-thrust belts may be excessively idealized. *The frequent use of well-designed computer programs may be somewhat overrated: their implied accuracy and respect for a limited number of deformation options tends to camouflage the many very real uncertainties that are associated with an inadequate definition of the basement and its nature, stratigraphic thickness assumptions, velocity assumptions used for depth conversions, and, most important, a firm anchor in the undeformed foreland. This has led to a formal stylization of foreland folded belts that is characterized by the endless replication of a few simple themes that hides the incredible variability of different styles in various foreland folded belts.*

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