BURNHAM'S CELESTIAL HANDBOOK

An Observer's Guide to the Universe Beyond the Solar System

Robert Burnham, Jr.

In Three Volumes

Volume Three, Pavo Through Vulpecula

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An Observer's Guide to the Universe Beyond the Solar System

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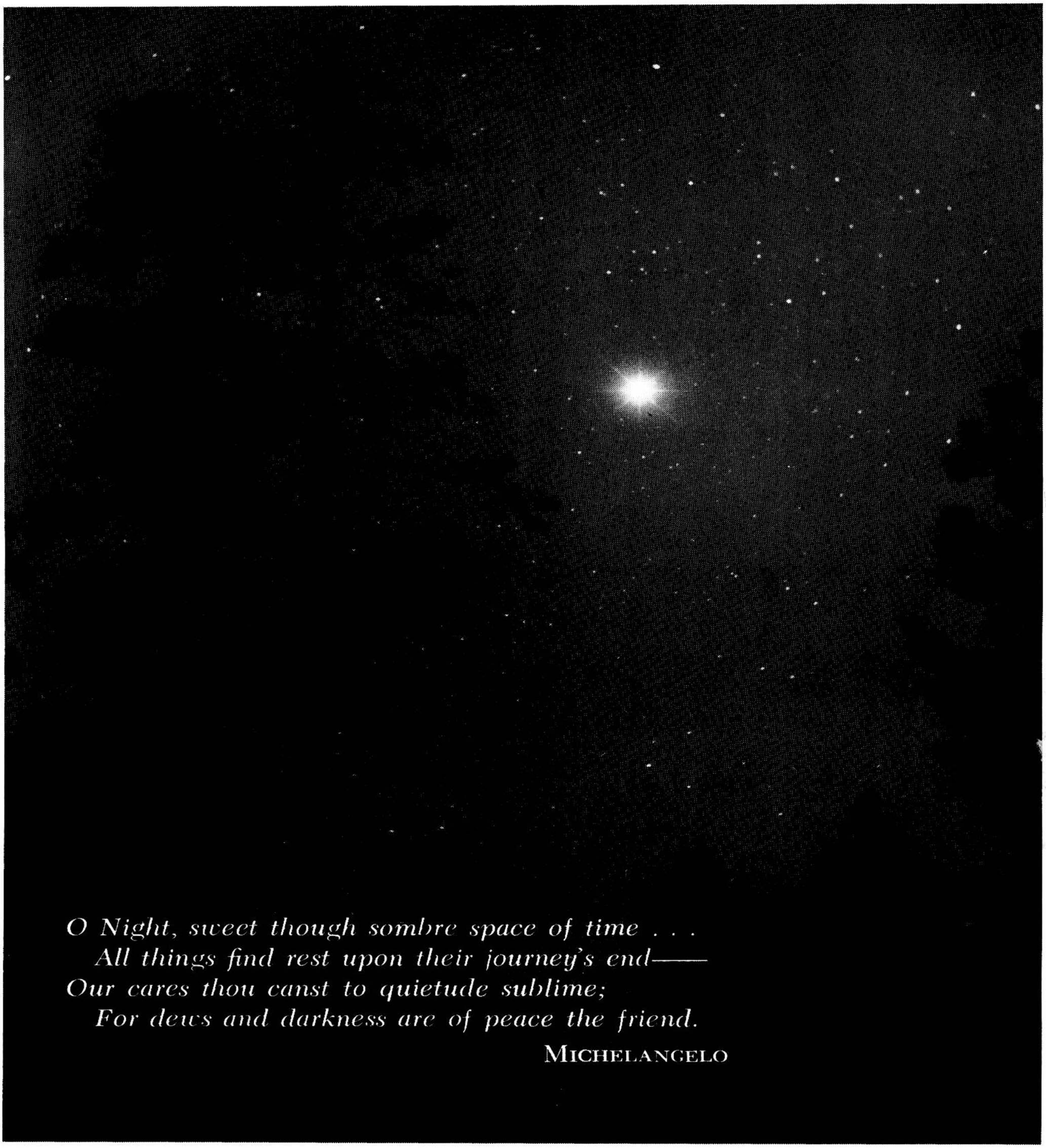
O Night, sweet though sombre space of time . . .
All things find rest upon their journey's end——
Our cares thou canst to quietude sublime;
For dews and darkness are of peace the friend.
MICHELANGELO

To Renata, Ivana and Ján

Preface

This book aims to provide a comprehensive understanding of thrustbelts as a whole. The aim is to synthesize existing information devoted to specific aspects of these important hydrocarbon habitats. The book assembles this information in one volume, in a manner that permits the knowledge to be used to assess the risks of exploring and operating in these settings.

The plan for this book originated with a project called *Systematics of Hydrocarbon Exploration and Production in Thrustbelts*, which summarized various aspects of exploration and production in thrustbelt settings provided by a large and diverse literature, and addressed gaps in knowledge.

This synthesis is completed from results of personal, long-term research on thrustbelts, numerical validations of various concepts and extensive tables documenting various factors influencing structural styles, thermal regimes and petroleum systems, as well as rates of various modern geological processes. The book contains an enclosed database on characteristic features of existing hydrocarbon fields in thrustbelts, which serves as further documentation. This book should have value to a broad range of readers, from geology students to exploration managers searching for the character of producing fields in analogous settings. The book is divided into four parts.

Part I defines the scope of the book, with the thrustbelt being defined broadly enough to include conventional thrustbelts, transpressional ranges, toe thrusts and accretionary prisms. It describes fundamental structural styles and variation of styles in thrustbelts, illustrated by worldwide thrustbelt data, including their location, age, tectonic character and vergency. The text follows with descriptions of the thrust wedge development, covering the two-dimensional frictional Coulomb wedge model, its limitations, its extension to three dimensions and additions to handle the brittle–ductile transition. The section on wedge mechanics is followed by thrust sheet mechanics, focusing on the rheological-stress control of the resultant thrust structures and the energy balance behind the chance that the active thrust sheet witnesses the propagation of a new thrust sheet, whether it experiences reactivation of existing faults, whether it undergoes further movements or whether it experiences internal deformation. Sandbox modelling and examples from the Taiwan thrustbelt and the West Carpathians, for example, document the role of the energy balance on complex thrust fault activity, including numerous out-of-sequence thrusting events. Subsequent chapters of the first part define thin- and thick-skin structures in thrustbelts, stress control on development, the importance related to hydrocarbon accumulation and the potential translation under subsequent shortening. These chapters are illustrated with geological cross sections, outcrop photographs and seismic data. The part concludes with descriptions of available methods for determination of thrust timing and related deformation rates.

Part II focuses on the importance of various factors controlling the structural architecture of thrustbelts. It was written with specific questions in mind. How do pre-existing structures affect the evolving structural style? What is the role of sedimentary rheology in the evolving structural style and which geological factors are most important in this role? How can knowledge of these factors be used to constrain geometric interpretations of structures? How do fluids influence the structural architecture, what are the fluid mechanisms in thrustbelts and how does one determine fluid sources, sinks and overpressure-buildup mechanisms?

Part II draws from physical phenomena described in Part I and analyses the importance of large-scale influencing factors. Sedimentary rheology is broken down into factors such as the relative strength of the rocks involved, rock lithification stages and how rocks are organized in the stratigraphic package by means of individual layer strengths, layer thicknesses, layer patterns and friction along their contacts, illustrated by extensive rock mechanics tables and factor interaction calculations. The text also focuses on rock layers undergoing deformation, how this may control reservoir horizons and trap geometries that could result from various combinations of rheologies and stress regimes. Fault-prone sequences become shortened by fault-bend folds, basement uplifts or inverted grabens. Sequences with upper weak layers and underlying stronger layers enhance the potential for passive roof duplexes, whereas little strength difference combined with high basal friction enhances foreland-vergent structures. Fold-prone sequences undergo detachment folding. Examples such as those from the Bolivian sub-Andean thrustbelt document how orogen strike-parallel changes in lithostratigraphy of accreted sediments can account for varying structural architecture under the same stress regime. A simple stress control argument indicates why the large number of interpreted fault-propagation folds may be faulted detachment folds. Numerical models and global examples document controls on the relative locations of detachment faults.

The text describes how the combination of rheology and stress in control of structural architecture becomes complicated in the upper 10–15 km of the crust, which contains pre-existing structures. It also explains how syntectonic deposition and erosion introduce further complexity. Modern-day rates of deposition and erosion from various thrustbelt settings are illustrated in extensive tabulated databases. The contribution of erosion and deposition resides not only in their effect on the thrustbelt itself, but also on the sediments to be accreted later, which in turn affect the thrustbelt development during accretion. Thick foreland sediments enhance the width and advance distance of the thrustbelt whereas thin sediments promote its internal deformation. Variable distribution of syn-tectonic sediments, together with variable sedimentary taper of the foreland basin, may produce a spectrum of structural styles, due to varying thrust spacing, various thrust trajectories and strength contrasts.

The text on fluid flow identifies the topography-driven/compaction-driven fluid flows as the main fluid flow mechanisms in thrustbelts. Although thrustbelts contain a variety of fluid sources, only compaction-released fluids, release of the structurally bound water from smectite, fluids produced by the gypsum-to-anhydrite transformation and hydrocarbon expulsion account for overpressure generation controlling the structural architecture. Fault cores sandwiched between high-fracture density damage zones are the most likely fluid migration paths in active thrustbelts with a tendency to collapse after their movement stops. The fluid flow along main detachment faults and ramps typically has a transient character.

Part III focuses on the importance of various factors controlling thermal regimes in thrustbelts. It addresses the following questions. What are the effects of pre-orogenic heat flow on subsequent thermal regimes? What are the effects of deformation on thermal regimes? What are the roles of stratigraphic development in thermal regimes, via thermal conductivity, specific heat and radioactive heat production? How does stratigraphic distribution affect the thermal regime? What are the roles of various fluid flow mechanisms in perturbing thermal regimes? How can the advective component of the heat transport be recognized? What are the roles of deposition and erosion in thermal regimes?

Part III builds on extensive tables of modern movement rates of plates and thrust sheets, and data sets on thermal conductivity, thermal diffusivity, specific heat capacity and heat production of rocks involved in thrustbelts. The review of natural slip rates for thrust sheets shows a characteristic range of 0.3–4.3 $mm\,yr^{-1}$, documented by minimum values from the Wyoming thrustbelt, the Perdido foldbelt in the Gulf of Mexico and the Argentinean Precordillera, by intermediate rates from the Pyrenees and the North Apennines, and by maximum rates from the San Joaquin basin and the Swiss Molasse basin.

Part III identifies, also drawing from new numerical modelling, the order of importance of various factors on thermal regimes. The list starts with factors as important as the presence or absence of syn-tectonic deposition/erosion, the pre-tectonic heat flow and the presence of critical fluid flow regimes. The part follows with factors such as the thermal blanketing potential of the uppermost layers of the accreted sequence, the slip rate, the accreted sequence lithology, the basal frictional heat and the radiogenic heat. The list ends with the lithology of detachment horizons and internal strain heating. Discussed perturbations in thrustbelts indicate that the thrust displacement of rock layers characterized by different heat production produces vertical and lateral thermal gradients.

Among fluid flow mechanisms, only the topography-driven and compaction-/compression-driven fluid flows are capable of affecting the thermal regime of a thrustbelt more than locally. The impact of both mechanisms is important because the flow rates can be greater than 10 $m\,yr^{-1}$. While the topography-driven flow is generally robust enough to achieve such flow rates, the compaction-/compression-driven flow usually requires a flow enhancement, such as flow focusing by faults. The advective component of the heat transport in thrustbelts is recognized either by analytical calculations or by analysis of maturation data. The surface heat flow in thrustbelts also responds quickly to deposition and erosion, but recovers slowly after the end of activity. Whereas the erosion increases the surface heat flow, the heat flow is significantly depressed by deposition rates equal to or greater than 0.1 $mm\,yr^{-1}$. The deposition can also depress the heat flow due to overpressure development. Examples (e.g., Kura basin in Azerbaijan) document that this phenomenon is caused by retarded heat transfer through undercompacted sediments.

Part IV focuses on the importance of various factors controlling petroleum systems in thrustbelts. It emphasizes the following questions.

What factors control the deposition and quality of source rocks in thrustbelts? What factors control the initiation and termination of hydrocarbon expulsion? What factors impact hydrocarbon migration, and how? What types of traps dominate in thrustbelts? What kinds of lithological seals are typical in thrustbelts and what factors control their sealing quality? What types of fault seals are typical in thrustbelts and what factors control their sealing quality? What factors enhance and destroy reservoir rocks, and how? What is the optimal timing for operation of the petroleum system?

Part IV discusses the critical presence of quality source rocks in correct stratigraphic and structural positions to have reached maturity near the close of, or following, thrusting. For example, burial beneath about 2 km of sediments shed into the Green River basin from the flanking Paleocene–Eocene Rocky Mountain uplifts was responsible for the post-thrust hydrocarbon generation from the Lower Cretaceous foreland basin source rocks in the Late Cretaceous Wyoming–Utah thrustbelt. However, source rock distributions in thrustbelts show a large variety of depositional settings and source rock quality and the magnitude of hydrocarbon reserves also vary. Generally, the deposition of source rocks is independent of the tectonic events that led directly to thrusting, but specific depositional settings appear to favour both quality source rocks and eventual contractional tectonics. These include eustatically flooded passive margin basins, silled pull-apart basins and synorogenic foreland basins. Typically, oil-prone black shales are deposited in the distal portions of the basins and gas-prone, coaly rocks characterize the proximal parts of the basins.

Rapid burial associated with thrust imbrication, followed by rapid post-thrusting rebound and erosion, perturb thermal gradients and complicate source rock maturation. Thrusts and associated fracture systems serve as conduits for migration of hydrocarbons and connate waters from the hydrocarbon kitchens to traps, and for the inward flux of meteoric waters that in time flush or degrade pooled hydrocarbons. Rock deformation and fluid migration during thrusting both enhance and degrade the quality of reservoirs. The majority of hydrocarbon fields reside in broad, simple anticlines in parts of thrustbelts where overall shortening and internal strains are relatively small. These folds are dominantly detachment and fault-propagation folds with a large radius of curvature in cross section (e.g., the Zagros foldbelt in Iran, the sub-Andean thrustbelt in Bolivia and Argentina, and the Wyoming thrustbelt). Additional traps are located in fault-seal-dependent footwall traps and sub-thrust autochthonous and para-autochthonous strata beneath the leading edges of thrustbelts.

Part IV also examines the worldwide distribution of oil and gas resources and the interplay of factors in thrustbelt settings to generate, entrap and preserve hydrocarbons. Many thrustbelts host hydrocarbons. A few are the site of world-class oil and gas accumulations. About a dozen thrustbelts hold the lion's share of hydrocarbon resources within this habitat. The strong asymmetry in the global distribution of hydrocarbon reserves in thrustbelts is examined here.

There is good reason to believe that thrustbelts will be productive sources of hydrocarbons well into the future. The opportunities include pure frontier plays, but extending exploration into less mature portions of established petroleum provinces is a safer path. This includes searching for deeper targets, smaller and unconventional traps, and by-passed resources. Many new technical tools are now available to assist in the discovery of new oil and gas, or in the more efficient recovery of known reserves. This book closes by pointing to likely directions of continued hydrocarbon exploration and development in thrustbelts. It seems clear that as world consumption of, and thus demand for, hydrocarbons continues to rise (BP, 2004), the 'real' price of the product will inevitable increase, thus funding the advances in technology that will be required for exploration and production of the future. We hope that this book will serve as a useful companion for those involved in this endeavour.

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PART ONE

Fundamentals of Thrustbelts

1 Introduction to the topic of thrustbelts

For the purposes of this book the term 'thrustbelt' is given a broad meaning to encompass any deformed belt in which contractional or transpressional brittle and brittle/ductile structural styles dominate over other types of structures, including conventional thrustbelts, transpressional ranges, toe thrusts and accretionary prisms (Figs. 1.1–1.6, Tables 1.1–1.6).

Conventional thrustbelts

Conventional thrustbelts evolve out of either passive margin or intracratonic rift systems and their consequent sedimentary basins (Fig. 1.7). Examples of passive margin sediments involved in a thrustbelt are seen in the Appalachians, Andes or Alps. Examples of orogenic belts evolved out of intracratonic rifts are the Atlas Mountains, Palmyrides or the northern Andes. The rift systems, whether of pure extensional or transtensional origin, form the fundamental crustal weaknesses that focus compressional stress and provide the volume of rocks that subsequently become incorporated into the thrustbelt. Nice examples of extensional and transtensional rifts later involved in thrusting come from the Urals. Their different geometries in relation to the direction of compression determined different structural styles in different parts of the Urals. Passive margin basins, with their broad post-rift sedimentary prisms tapering out onto the nonrifted cratons favour '*thin-skin*' structural styles in which the sedimentary cover strata are detached and deformed independently of the underlying basement (Fig. 1.8). Intracratonic rift systems, on the other hand, tend to produce '*thick-skin*', or basement-involved thrustbelts in which inverted half-grabens or uplifted basement blocks are a dominant feature (Figs. 1.9 and 1.10). However, the distinctions between thin- and thick-skin thrustbelt styles are not rigid. Even in the thin-skin variety, the basal thrust surfaces root within displaced basement elements, many of which can be demonstrated to have been older normal faults (Fig. 1.11). Elements of thin-skin styles are frequently encountered in inverted graben systems, especially where salt or thick shale deposits flank the precursor intracratonic basin. A nice example of the salt thickness controlling thin-skin versus thick-skin structural style comes from the inverted Broad Fourteens basin in the North Sea.

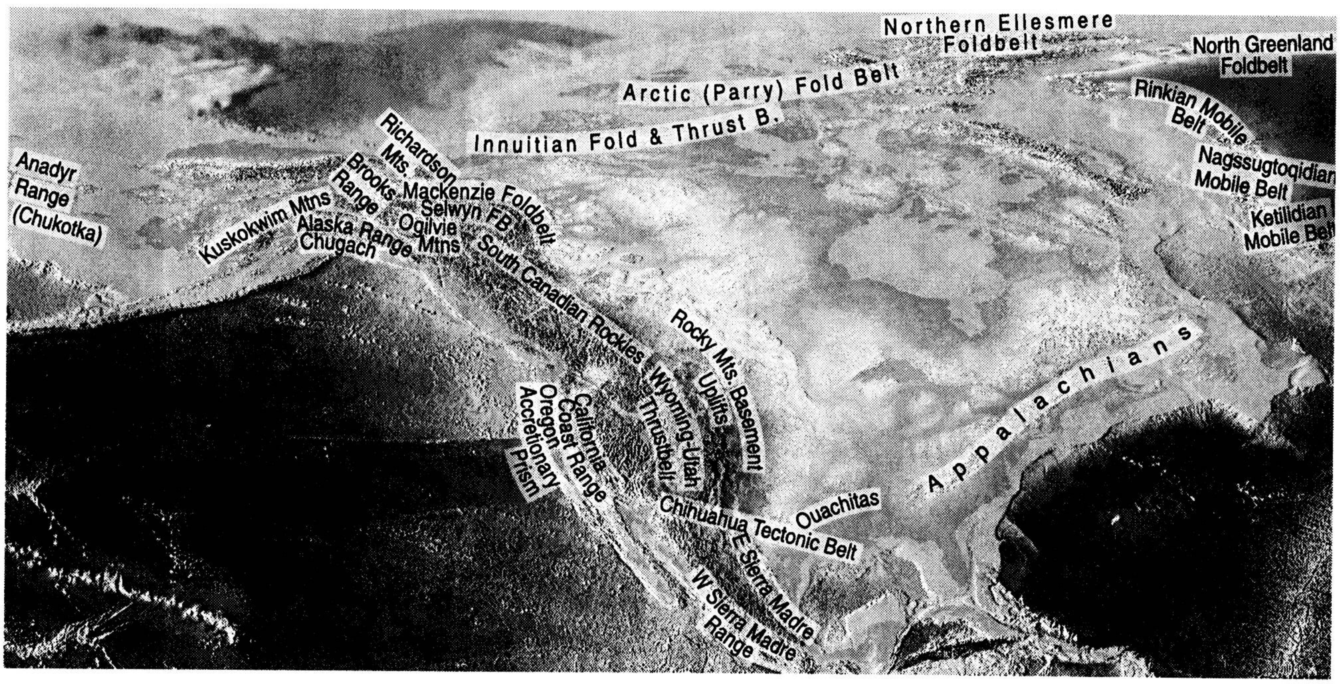

Fig. 1.1. Thrustbelt map of the North American continent. The topographic map is taken from Smith and Sandwell (1997).

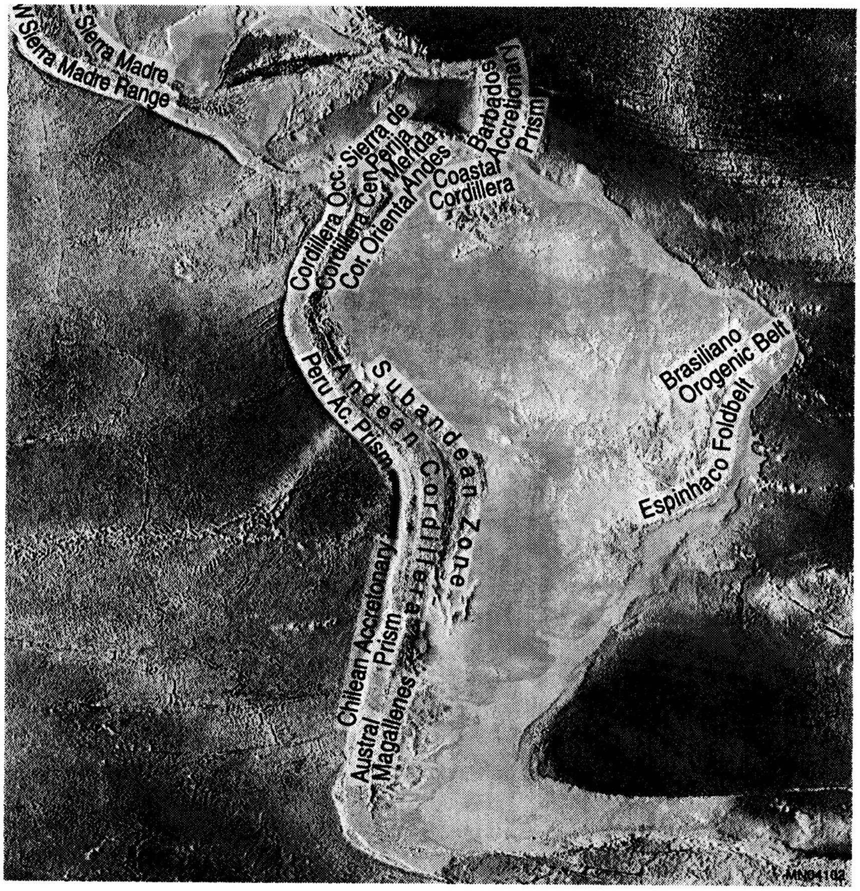

Fig. 1.2. Thrustbelt map of the South American continent. The topographic map is taken from Smith and Sandwell (1997).

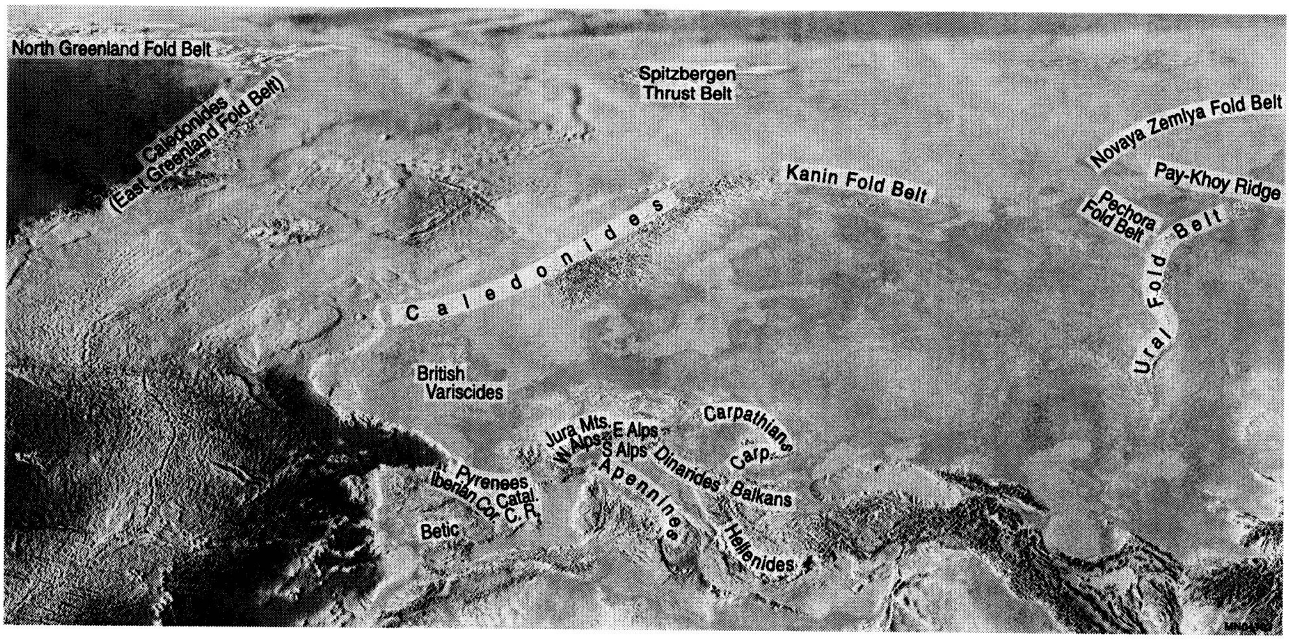

Fig. 1.3. Thrustbelt map of Europe and adjoining North Africa. The topographic map is taken from Smith and Sandwell (1997).

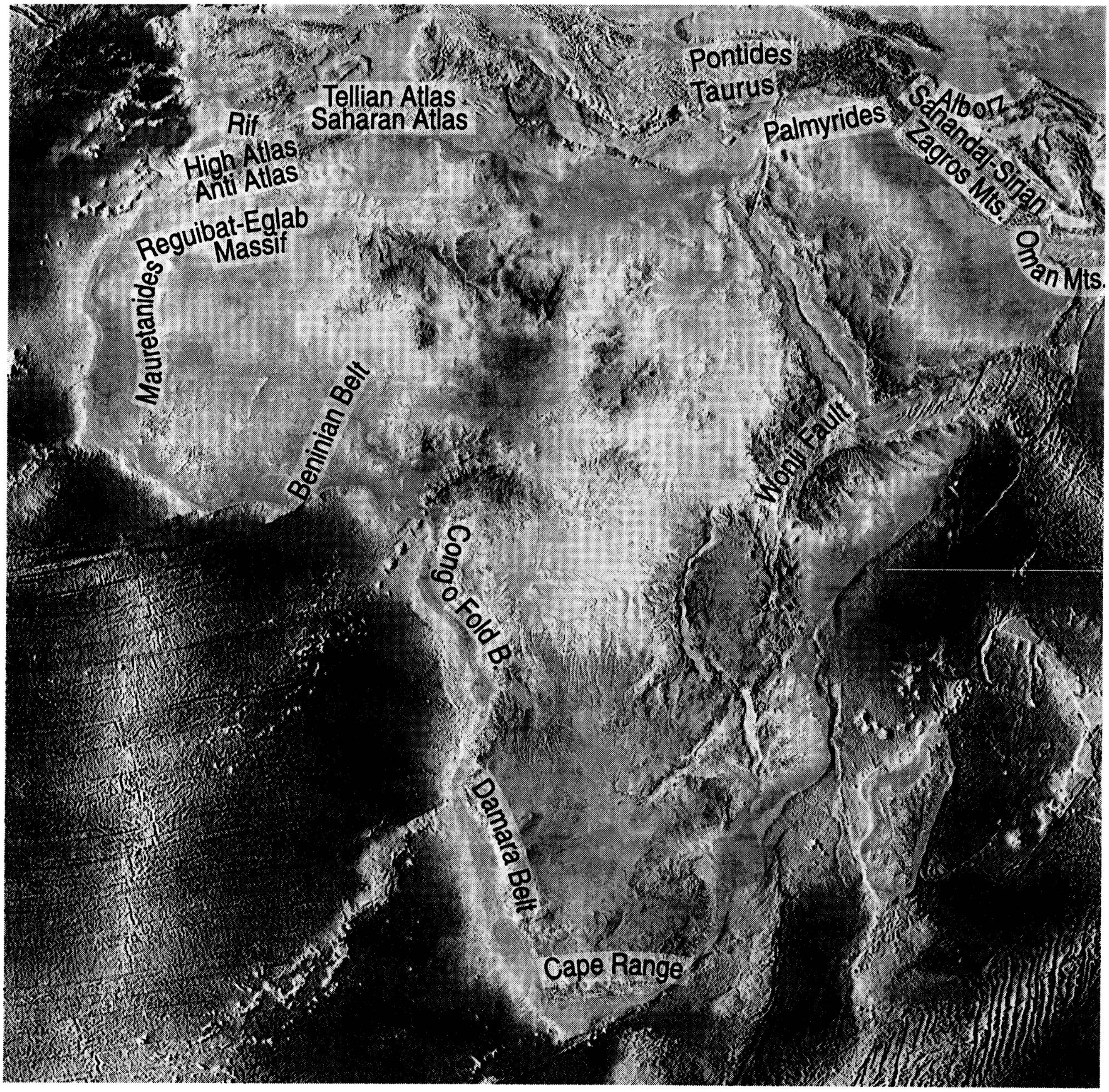

Fig. 1.4. Thrustbelt map of the African continent. The topographic map is taken from Smith and Sandwell (1997).

For a conventional thrustbelt to develop, basement rocks must be shortened somewhere within the width of the belt. In some instances, this involves partial restoration of the extension accompanying rifting, resulting in an inverted rift system (Fig. 1.9). In other cases the shortening results in contractional translation of the original rift elements for very large distances and the generation of thin-skin structural styles where the thrusts cut up into and displace thin slabs of the sedimentary cover (Fig. 1.12). Many thrustbelts exhibit both thin- and thick-skin structural styles in different portions of the belt (Figs. 1.13a and b). Some, such as the Andes, change style along strike (Fig. 1.13a; Allmendinger *et al.*, 1997), whereas others, such as the US Cordillera-Rocky Mountains, exhibit thin-skin styles in their interior and inverted basement styles in their exterior (Fig. 1.13b; Hamilton, 1988), or vice-versa.

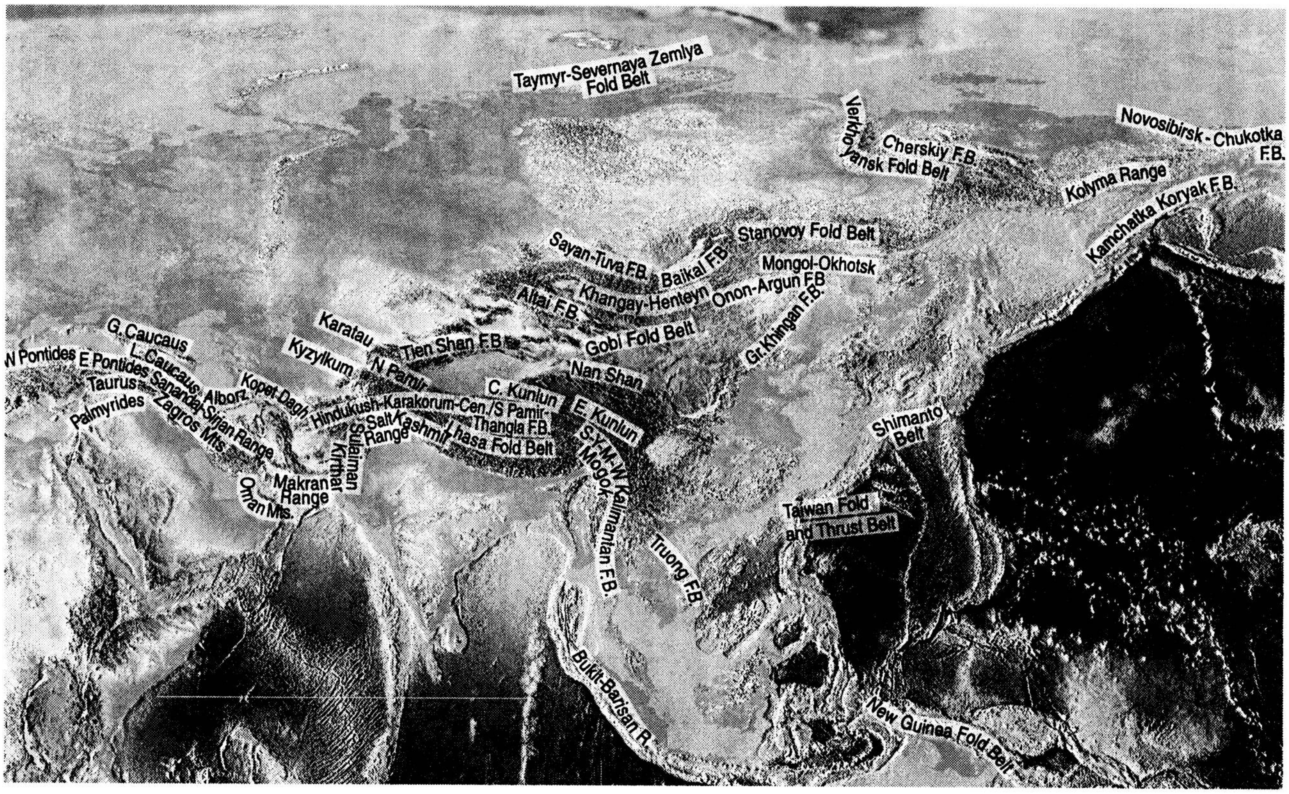

Fig. 1.5. Thrustbelt map of the Asian continent. The topographic map is taken from Smith and Sandwell (1997).

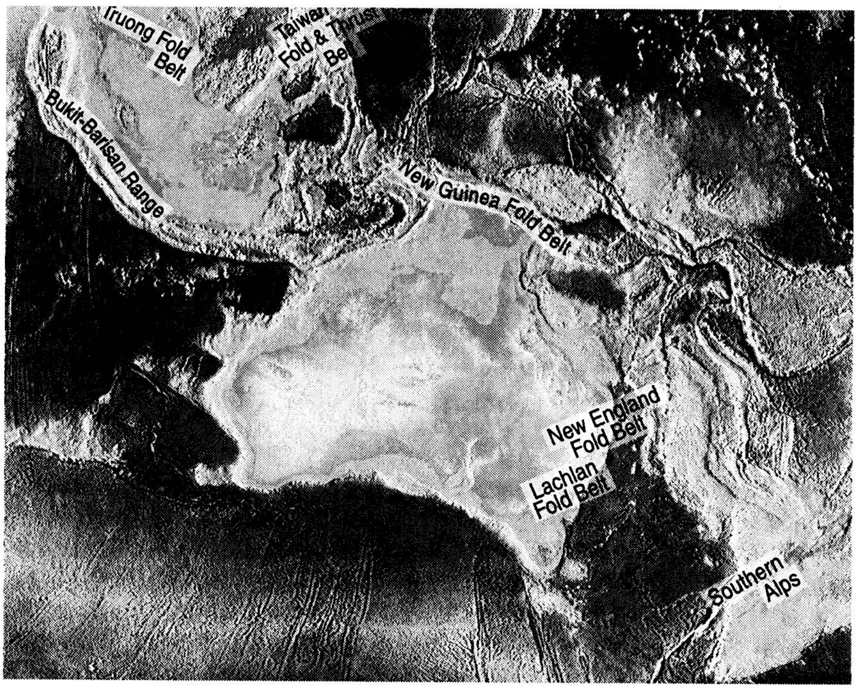

Fig. 1.6. Thrustbelt map of the Australian continent. The topographic map is taken from Smith and Sandwell (1997).