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Thrust-breakthrough of asymmetric anticlines: Observational constraints from surveys in the Brooks Range, Alaska

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ABSTRACT

To gain insights into the processes governing the thrust-truncation of anticlines, we conducted a field study of the thrust-truncated folds in the remote Brooks Range of northern Alaska, where there is a transition in fold style from symmetric detachment folds to thrust-truncated asymmetric folds. In order to document the detailed geometry of the km-scale folds exposed in cliff-forming, largely inaccessible outcrops, a new surveying technique was developed that combines data from a theodolite and laser range finder. The field observations, survey profiles, and cross section reconstructions, indicate that late-stage thrust breakthrough of the anticlines within the mechanically competent Lisburne Group carbonates accommodated continued shortening when other mechanisms became unfeasible, including fold tightening, forelimb rotation, and parasitic folding in the anticline forelimbs. These results provide constraints on the processes that govern the transition from buckle folding to thrust truncation in fold-and-thrust belts worldwide.

1. Introduction

Asymmetric folds underlain by thrust faults are a common feature of fold-and-thrust belts worldwide, for example in the Pyrenees in Spain (Poblet et al., 1998), the Zagros Mountains in Iran (McQuarrie, 2004; Sherkati et al., 2005), the western foothills of Taiwan (Suppe, 1981), the Canadian Rockies (Price, 1981), and the Mississippi Fan foldbelt in the Gulf of Mexico (Rowan, 1997). The correct interpretation of fold geometry and origin is important for the reconstruction of unknown parts of structures, including the interpretation of seismic data and the assessment of petroleum traps in industry.

The three major types of thrust-related folds in fold-and-thrust belts are fault-bend folds, fault-propagation folds, and detachment folds. A fault-bend fold is a hangingwall anticline that forms as beds in the hangingwall are displaced over the bend between the footwall ramp and upper footwall flat (Suppe, 1983; Jamison, 1987). A fault-propagation fold is a hangingwall anticline that forms to accommodate slip ahead of an underlying and upward-propagating ramp tip (Jamison, 1987; Mitra, 1990; Suppe and Medwedeff, 1990; Erslev, 1991; Fisher and Anastasio, 1994). A detachment fold forms when a competent unit folds above an incompetent unit to accommodate slip along a basal decollement, and commonly forms by buckling (Jamison, 1987; Wallace, 1993; Epard and Groshong, 1995; Homza and Wallace, 1995; Poblet and McClay, 1996; Thorbjornsen and Dunne, 1997; Mitra, 2002; Atkinson and Wallace, 2003).

A hangingwall ramp is inherent to the initial formation of fault-bend and fault-propagation folds, with the thrust being oriented at a high angle to bedding in the anticline forelimb (Suppe, 1983; Jamison, 1987; Suppe and Medwedeff, 1990). This is not the case in detachment folds, where the basal decollement is commonly not seen and remains within the incompetent unit during fold growth in the competent strata (Jamison, 1987; Homza and Wallace, 1995; Poblet and McClay, 1996; Homza and Wallace, 1997). However, a detachment fold or any buckle fold can display a hangingwall ramp if a fold limb in the competent unit is truncated subsequent to initial fold formation (Thorbjornsen and Dunne, 1997; Wallace and Homza, 2004).

Early models recognizing the thrust truncation of previously formed anticlines include the Willis (1893) break-thrust model, in which thrust-breakthrough eventually becomes less difficult than continued folding (Willis, 1893; Fischer et al., 1992), the stretch thrust model, in which the thrust truncates a previously overturned and attenuated anticline forelimb (Heim, 1919), and a model similar

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to the break-thrust model in which the thrust fault truncates the upright anticline forelimb to accommodate space problems within the fold (de Sitter, 1964). Despite this early recognition, truncated buckle folds and truncated detachment folds remain under-recognized and are commonly misinterpreted in the field (Thorbjornsen and Dunne, 1997; Wallace and Homza, 2004), and the factors that favor their formation and the processes by which they form remain unclear (Fischer et al., 1992; McNaught and Mitra, 1993; Mitra, 2002). The detailed documentation of the geometry of such folds and faults is the first step toward assessing their origin and evolution.

Spectacular examples of thrust-related folds occur throughout the northern Brooks Range of northern Alaska, where folds with wavelengths of a kilometer and greater are exposed (Fig. 1). These folds are formed in competent carbonates of the Lisburne Group which overlie the incompetent Kayak Shale (Wallace and Hanks, 1990; Wallace et al., 1997). In the northeastern Brooks Range, the Lisburne Group forms intact, upright, symmetric detachment folds (Wallace and Hanks, 1990; Wallace, 1993; Homza and Wallace, 1995, 1997; Atkinson and Wallace, 2003). To the south in the central and eastern Brooks Range, the Lisburne Group carbonates typically form north-vergent, asymmetric thrust-truncated folds, and less commonly, upright non-truncated folds (Glenn, 1991; Wallace et al., 1997; Grischkowsky, 2002; Wallace and Homza, 2004).

In order to document the detailed fold geometry in this region and identify controls on the transition from intact detachment folds to thrust-truncated folds, we conducted a field study of the kilometer-wavelength folds in the eastern Brooks Range, at the juncture between symmetric detachment folds to the north and thrust-truncated asymmetric folds to the south (Fig. 1). The study area is located in the upper Marsh Fork (UMF) of the Canning River, in the Arctic National Wildlife Refuge (Fig. 1). An advantage of conducting a study quantifying fold geometry in the Brooks Range is that the outcrops span over a kilometer of relief (Atkinson and Wallace, 2003). Thus, the data are from exposed folds, rather than from seismic reflection data on subsurface folds (Guzofski et al., 2009; Soleimany et al., 2011). In order to obtain data from outcrops of this scale, we developed a surveying technique that enabled the remote access of structural data from the cliff-forming outcrops.

In this paper, we present combined survey and traditional structural attitude data collected in the field to quantify the geometry of ten folds in detail. These field observations provide constraints on the processes that govern the transition from buckle folding to thrust truncation in the Brooks Range and can

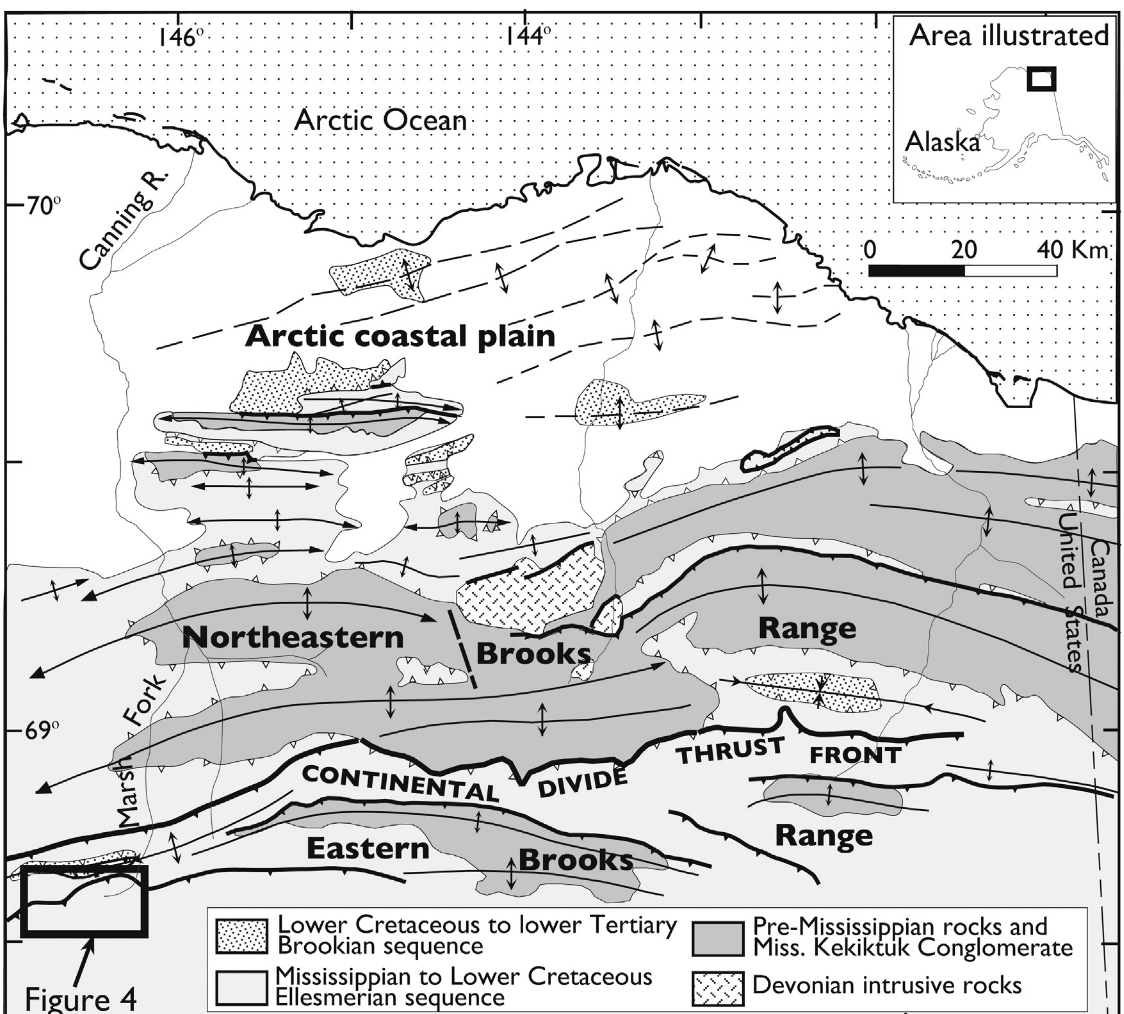

Fig. 1. Generalized tectonic map of the eastern and northeastern Brooks Range, Alaska. The Continental Divide thrust front separates the northeastern Brooks Range, to the north, from the eastern Brooks Range, to the south. Black box in lower left shows location of UMF field area shown in Fig. 4. Modified from Wallace and Homza (2004).