Marine and Petroleum Geology 46 (2013) 144–164

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Fluid flow in relay zones revisited: Towards an improved representation of small-scale structural heterogeneities in flow models

Muhammad Fachri[a,b,*], Atle Rotevatn[a,b], Jan Tveranger[a]

[a] Uni Centre for Integrated Petroleum Research (CIPR), PO Box 7810, N-5020 Bergen, Norway
[b] Department of Earth Science, University of Bergen, Allégaten 41, N-5007 Bergen, Norway

ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form
17 May 2013
Accepted 22 May 2013
Available online 6 June 2013

Keywords:
Fault
Deformation band
Damage zone
Fault facies
Reservoir modelling
Upscaling
Reservoir simulation
Sweep efficiency

ABSTRACT

Soft-linked relay zones may act as conduits for fluid flow across otherwise sealing fault zones; yet, relay zones are commonly also associated with a structurally complex linking damage zone, which in sandstone reservoirs may include low-permeable deformation bands. Incorporating such mm- to cm-scale baffles in flow models is important in order to understand the total effect of relay zones on cross-fault flow. Given the small-scale nature of deformation bands, well below the resolution of conventional reservoir models, their implementation requires implicit representation and upscaling. By applying a deterministically constrained stochastic approach using truncated Gaussian simulation (TGS), we generate reservoir models which closely reproduce observed structural geometries and spatial distribution patterns. Flow simulations of the stochastically generated models, where deformation band permeability is the main variable tested, are compared with the deterministic approach of a previous study of the same relay zone. Our comparison shows that contrasting flow behaviour in the stochastic and deterministic models is amplified as the ratio between host rock and deformation band permeabilities increases. Increasing this ratio causes increased fluid flow complexity in the relay zone and enhances differences in sweep efficiency between the stochastic and deterministic models. Reservoir performance on several model realizations show that time to water breakthroughs in the stochastic models can be 18% shorter whereas their total productions can be 23% lower. The results of the present study indicate that the TGS approach is well suited to capture the details of fluid flow in the presence of small-scale reservoir heterogeneity with intermediate to high permeability contrast relative to host rock (here, 3 to 5 magnitude orders). This has implications not only for the modelling of relay zones, but also for the modelling of other reservoir settings where small-scale (structural) heterogeneity is present.

1. Introduction

Faults may profoundly influence subsurface fluid flow patterns, including routing of hydrocarbons from source kitchen to trap, containment of hydrocarbons in fault-controlled structural traps, and internal compartmentalization and baffling of intra-reservoir fluid flow during production. Rendering fault architecture and properties in a manner that captures these effects correctly is therefore a priority when constructing reservoir models for forecasting purposes. The present paper addresses aspects of fault implementation in such models by comparing different methods for capturing soft-linked relay zones and associated small-scale structural damage in flow models. This is done through an outcrop analogue and flow modelling study of a soft-linked relay zone in Arches National Park, Utah (Fig. 1).

1.1. Fault growth and the evolution of relay zones

The process of fault evolution through the growth, linkage and amalgamation of initially separate fault segments into longer, continuous faults is amply documented and relatively well-understood (e.g. Peacock and Sanderson, 1991, 1994; Trudgill and Cartwright, 1994; Cartwright et al., 1996; Cowie et al., 2005; Fossen et al., 2010). Fault linkage occurs as initially unconnected fault segments grow through stages of underlap

Abbreviations: AFP, average field pressure; TGS, truncated Gaussian simulation; TWBT, time to water breakthrough; k_{db} (in relation to models or cases), deformation band permeability.

* Corresponding author. Uni Centre for Integrated Petroleum Research (CIPR), PO Box 7810, N-5020 Bergen, Norway. Tel.: +47 94176194.
E-mail address: muhammad.fachri.1973@gmail.com (M. Fachri).

0264-8172/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpetgeo.2013.05.016

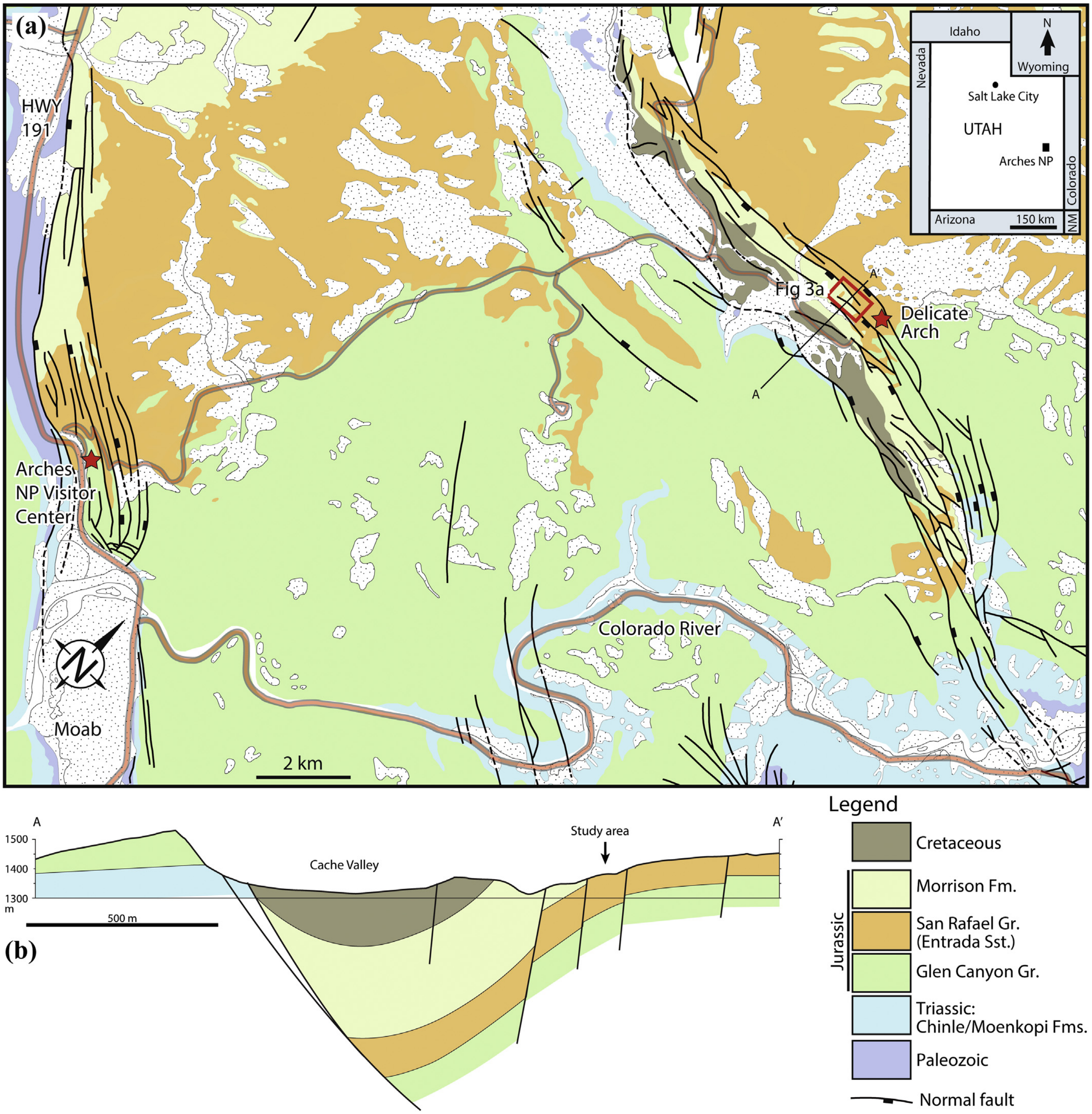

Figure 1. (a) Map of Arches National Park. The locations of cross section (b) and mapped area in Figure 3a are indicated. (b) Cross section from the study area. From Rotevatn and Fossen (2011), based on Doelling (2001) and Antonellini and Aydin (1995).

(Fig. 2, upper block), overlap (soft-linkage) (Fig. 2, middle block) and, eventually, hard-linkage and amalgamation of the segments into one continuous fault (Fig. 2, lower block) (Peacock and Sanderson, 1994; Imber et al., 2004). Soft-linked relay ramps are formed at an early stage, forming a zone across which strain is transferred between the overlapping fault segments through the folding (tilting) of continuous relay beds (Peacock and Sanderson, 1991). As the segments physically link, the relay zone is breached and the initially separate segments coalesce into a continuous fault (e.g. Imber et al., 2004; Ciftci and Bozkurt, 2006).

This view implies that soft-linked relay ramps are transient features in the progression of fault linkage. An alternative view is that, in cases where there is a strong control from pre-existing structural fabric, younger faults may establish their final lengths early on, with limited tip propagation only during subsequent further displacement accrual (the 'coherent fault model', e.g. Walsh et al., 2003; Giba et al., 2012). In such cases, relay zones may be longer-lived features, which may or may not progress to wholesale fault linkage during further fault growth (Giba et al., 2012). Regardless of which of these two models are preferred, previous work has shown that soft-linked and hard-linked relay zones are