

Structural style and hydrocarbon prospectivity in fold and thrust belts: a global review

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Abstract: A statistical analysis of reserves in fold and thrust belts, grouped by their geological attributes, indicates which of the world's fold and thrust belts are the most prolific hydrocarbon provinces. The Zagros Fold Belt contains 49% of reserves in fold and thrust belts and has been isolated during the analysis to avoid bias. Excluding the Zagros Fold Belt, most of the reserves are in thin-skinned fold and thrust belts that have no salt detachment or salt seal, are partially buried by syn- or post-orogenic sediments, are sourced by Cretaceous source rocks and underwent their last phase of deformation during the Tertiary. A significant observation is that the six most richly endowed fold and thrust belts have no common set of geological attributes, implying that these fold belts all have different structural characteristics. The implication is that deformation style is a not critical factor for the hydrocarbon endowment of fold and thrust belts; other elements of the petroleum system must be more significant. Other fold and thrust belts may share the structural attributes but the resource-rich fold belts overwhelmingly dominate the total reserves in that group of fold belts. There is nothing intrinsic in fold and thrust belts that differentiates them from other oil- and gas-rich provinces other than the prolific development of potential hydrocarbon traps. Many of the prolific, proven fold and thrust belts still have significant remaining exploration potential as a result of politically challenging access and remote locations.

This paper developed from a review of the geological characteristics of fold and thrust belts that contain hydrocarbons. The primary data source for this study is the International Exploration and Production Database marketed by IHS, which contains data on production and reserves for gas, oil and condensate on all producing and discovered fields around the world, excluding onshore North America. This is the most complete dataset available but it must be appreciated that the data are of variable quality. These data have been supplemented by information from the US Geological Survey World Petroleum assessments where they are available (USGS 2000). Information on the geological characteristics of the fold belts in this review has been derived from published literature.

The purpose of the paper is to analyse statistically the geological characteristics of hydrocarbon-productive fold and thrust belts. There have been few previous attempts to undertake this type of analysis (Graham *et al.* 1997) and most reviews of hydrocarbon potential are limited in geographical scope (e.g. Picha 1996; Brookfield & Hashmat 2001). The analysis presented here focused on a few selected key parameters that could potentially affect hydrocarbon prospectivity and reserves distribution.

The review of geological characteristics focused on structural style observations such as

whether the fold belt is thick or thin skinned, presence of a salt detachment, the presence of a salt seal and syn-orogenic burial. The depth to detachment and the thickness of the competent beam involved in the deformation were also noted but not analysed in detail because of the variable quality of the data for these factors. Time elements, such as the age of onset of the last deformation phase in the fold and thrust belt and the depositional age of the source rock, were also recorded and analysed. There are many other factors that could have been considered (e.g. pre-existing basement structures, source rock characteristics and age of source maturation). These other factors are also important but were beyond the scope of the dataset for this paper.

In this assessment a fold belt is considered to be any hydrocarbon province that is dominated by compressional tectonics resulting from plate convergence. Fold belts that have their origins as the contractional toes to extensional systems on continental margins have been excluded. These fold belts have become important hydrocarbon provinces as exploration drilling has moved out into deep-water continental margins (e.g. the deep-water Gulf of Mexico, deep-water Niger Delta and Brazil). This decision was taken because the fundamental tectonic driving mechanism is different from that in a convergent margin fold belt even though the geometric

characteristics are obviously very similar (Rowan *et al.* 2004).

The IHS dataset includes reserves information for discovered fields. It takes no account of the yet-to-find potential of the basins. The dataset was extracted from the IHS database in March 2004 and was then edited to remove all fields that were not located in fold and thrust belts.

Importance of fold and thrust belts as hydrocarbon provinces

Based on the IHS field reserves data, 14% of the world's discovered reserves are in fold and thrust belts developed at convergent plate boundaries, a significant proportion of the global reserve base. This percentage appears to be largely independent of hydrocarbon phase (Fig. 1a). The split of oil, gas and condensate indicates that the percentage of oil (59%) in fold and thrust belts is very similar to the percentage of oil (54%) in all global reserves (Fig. 1b). The conclusion is that the oil:gas:condensate ratio is roughly the same in fold and thrust belts as it is for all global

petroleum reserves. One of the difficulties in undertaking a statistical analysis of fold belts is that the dataset is dominated by the Zagros Fold Belt of Iran, Iraq, Syria and Turkey, which accounts for 49% of all the established reserves in the fold belts around the world.

The USGS global assessment of resources in 2000 concluded that fold and thrust belts amounted to 15% of the global total of undiscovered resources (USGS 2000). The implication is that as known fold and thrust belt reserves constitute 14% of global reserves, the yet-to-find is almost identically proportioned based on the tectonic setting. The conclusion is that fold and thrust belts represent an absolutely average sample of global hydrocarbon resources, there is nothing statistically distinctive about fold and thrust belts; they are oil prone because they are a very good sample of an oil-prone world.

Hydrocarbon discoveries in fold and thrust belts date back to the earliest days of oil exploration in the late 19th and early 20th centuries. The primary reason for these discoveries was that early drilling tended to focus on structurally simple anticlines that could be mapped using the surface geology, which mimicked the subsurface

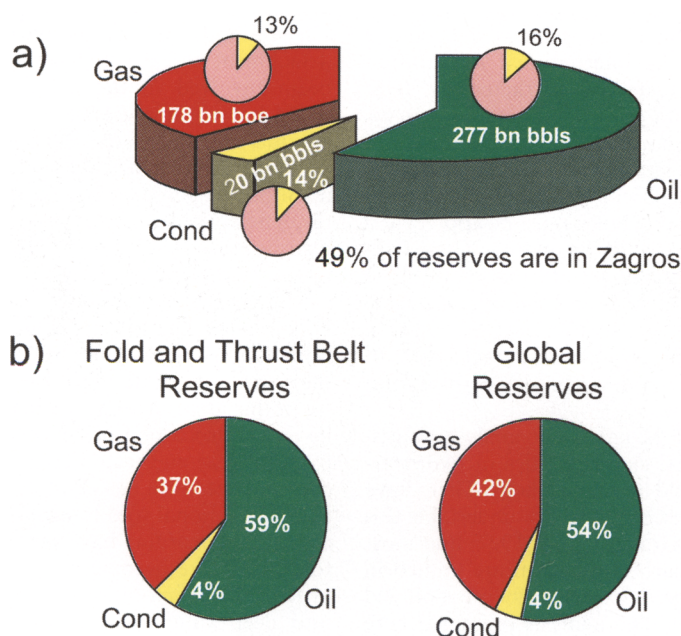


Fig. 1. (a) Distribution of hydrocarbon type in fold and thrust belts; total volumes are indicated on the pie chart segments. The yellow segments of the smaller pie charts indicate the proportions of global reserves in fold and thrust belts for each hydrocarbon type with the actual percentage labelled. **(b)** Comparison of hydrocarbon type split between fold and thrust belts and all global reserves.

structure at the reservoir level. This ultimately led to the discovery of super-giant oilfields in the Zagros Fold Belt of Iran and Iraq, such as Kirkuk, in the early decades of the 20th century. However, 80% of the giant fields were discovered after 1950 because of the challenges of exploring in structurally complex terrain. For example, in Wyoming the first discovery was in 1900, but it was not until the late 1970s that the first giant field (Whitney Canyon–Carter Creek) was discovered (Lamerson 1982). Structural complexity is a major problem when exploring many fold and thrust belts because the surface structural expression is commonly decoupled from the subsurface structural geometry at the reservoir level. Seismic imaging and ability to accurately map complex subsurface structures are therefore the keys to exploration. The reasons for geophysical exploration and field mapping are obvious, but structural and tectonic analysis can also improve risk assessment. Detailed structural analysis allows identification of prevalent geometric patterns of faulting and folding. Dahlstrom (1970), Boyer & Elliott (1982) and Suppe (1983) used structural analysis to establish general rules of structural cross-section interpretation. These rules, when combined with field and geophysical data, can tightly constrain the location, shape,

and size of structural traps (e.g. Cooper *et al.* 2004).

The Alberta foothills provide a well-documented example of how the evolution of structural models has affected exploration success over several generations (Gallup 1975; Ower 1975; Stockmal *et al.* 2001). Other examples are the Papua New Guinea fold and thrust belt (Hobson 1986; Hill 1991; Hill *et al.* 2004) and the Dagestan fold and thrust belt (Sobornov 1994). Revisions of structural model paradigms still continue to yield exploration success even in mature fold and thrust belts (e.g. in the Utah overthrust belt; Moulton & Pinnell 2005). The common progression in the exploration of most fold and thrust belts is from the exploration of the simpler, near-surface structures to the deeper, more complex, sub-thrust structures, which in many cases hold the larger prizes (e.g. the Alberta foothills; Gallup 1975; Ower 1975; Stockmal *et al.* 2001).

Fold and thrust belts included in this review

The 55 fold and thrust belts included in this review are shown in Figure 2 and Table 1. The reserves data in the IHS database are organized

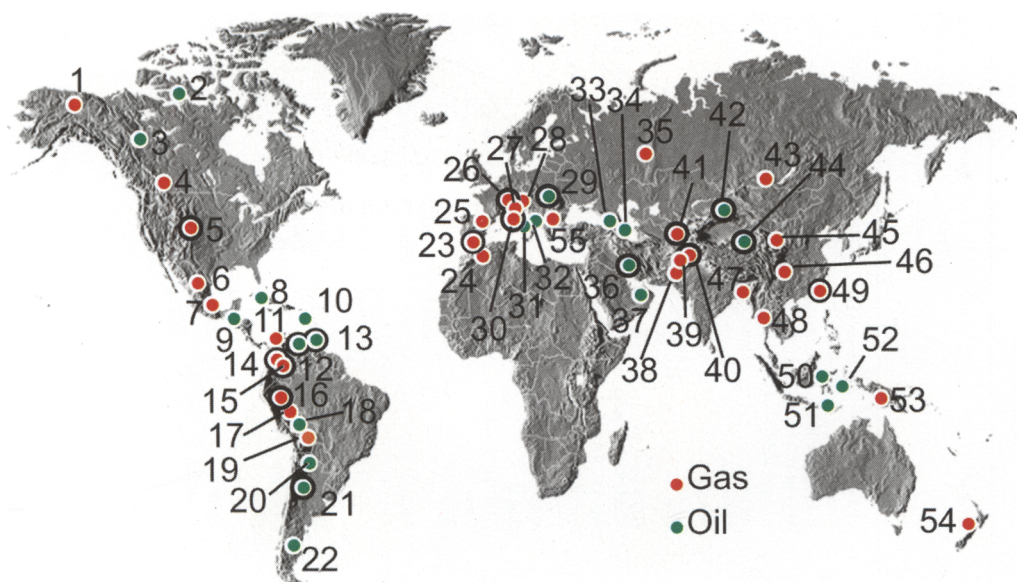


Fig. 2. Location map of fold and thrust belts included in this study. Each fold and thrust belt is labelled with a reference number that is included in Table 1. The locations are colour coded by the predominant hydrocarbon type, and those symbols that are outlined in black indicate fold and thrust belts that Mike Coward worked on during his career.

Table 1. Summary of data for fold and thrust belts

Fold belt	Country	Orogen	Thin or thick skinned	Buried	Salt seal	Salt detachment	Salt detachment age	Onset of last deformation	Competent beam (km)	Depth to detachment (km)	Source age	No. of belt in Fig. 2	Oil + Condensate (mm bbl)	Gas (mm boe)	Total reserve (mm boe)	Oil or Gas index
Altun Shan FB	China	Himalayan	Thick	No	Partial	No		Pliocene			Oligo-Miocene	44	664	554	1218	O
Arctic FB	Canada	Arctic	Thin	No	No	No		Palaeocene			Palaeocene	2	3	0	3	O
Assam FB	Bangladesh, India, Myanmar	Himalayan	Thin	No	No	No		Miocene	0	>5	Palaeocene	47	135	345	480	G
Atlas FB	Algeria, Italy	Atlas	Both	No	No	Yes	Trias	Eocene		10	Silurian	24	94	107	201	G
Balkan FB	Bulgaria	Alpine	Thin	No	No	No		Early Jur			Jurassic	55	0	0	0	G
Banggai FB	Indonesia	Banda Arc	Thin	No	No	No		Miocene	>3	>5	Oligo-Miocene	50	33	929	963	G
Beni FB	Bolivia	Andean	Thin	No	No	No		Miocene	0-1		Devonian	18	7	2	8	O
Betic FB	Spain	Alpine	Thin	No	No	Yes	Trias	Miocene			Late Miocene	23	0	0	0	G
Brooks Range	USA	Rockies	Thin	No	No	No		Early Cret			Jurassic	1	0	0	0	G
Carpathian FB	Poland, Ukraine, Czech R., Romania, Austria, Slovakia	Alpine	Thin	Partial	No	Partial		Miocene	1	>2	Oligocene	29	5643	1785	7428	O
Caucasus FB	Azerbaijan, Uzbekistan, Kazakhstan, Russia	Caucasus	Thick	Part/Yes	No	No		Miocene	2	6	Oligocene & Trias-Jurassic	34	26954	13973	40927	O
Chaco FB	Argentina, Bolivia	Andean	Thin	No	No	No		Miocene	1	5	Middle Dev	19	2033	12034	14067	G
Cuban FB	Cuba	Cuban	Thin	Yes	No	Yes	Jur	Miocene	1	5	Late Jurassic	8	378	10	388	O
Cuyo FB	Argentina	Andean	Thick	No	No	No		Miocene	>3	>10	Late Triassic	20	1673	80	1752	O
Dagestan FB	Russia	Caucasus	Thick	Partial	Partial	No		Miocene	2	6	Oligocene	33	3897	1386	5283	O
Dinarides	Albania	Alpine	Thin	Yes	No	Yes	Trias	Pliocene	1-4	>5	Mio-Pliocene	32	592	228	820	O
Eastern Alps	Austria	Alpine	Thin	Yes	Yes	Yes	Trias	Eocene	1-4	>2	Oligocene	28	6	41	47	G
Eastern Cordillera	Colombia	Andean	Thick/Thin	No/Yes	No	No		Miocene	0		Late Cret	14	7	9	16	G
Gissar FB	Uzbekistan, Tajikistan	Himalayan	Both/Thick	No	No/Part	No/Part		Miocene	1	10	Early Jurassic	41	1113	1347	2459	G
Guajira Prism	Colombia	Andean	Thin	Yes	No	No		Miocene	1		Unknown	11	0	67	67	G
Jura FB	France	Alpine	Thin	No	No	Yes	Trias	Miocene	1	3	Late Carb	26	0	1	1	G
Kirghar FB	Pakistan	Himalayan	Thin	No	No	No		Palaeocene	>5	10	Early Cret	38	0	278	278	G
Llanos Foothills	Colombia, Venezuela	Andean	Both/Thin	No	No	No		Miocene			Late Cret	15	2512	1275	3788	O
Loei-Phetchabun FB	Thailand	Himalayan	Thick	No	No	No		Late Cret	2	5-10	Triassic	48	1	180	181	G
Madre de Dios FB	Peru	Andean	Thin	No	No	No		Miocene	2	>5	Devonian	17	937	2879	3816	G
Malague-Agro FB	Argentina	Andean	Both	No	No	No		Miocene	1	5	Late Jurassic	21	481	242	723	O
Maturin FB	Venezuela	Andean	Thin	Yes	No	No		Miocene	2	5	Late Cret	12	22612	17370	39982	O
NE Caribbean FB	Barbados	Caribbean	Thin	No	No	No		Pliocene			Eocene	10	13	4	18	O
New Zealand	New Zealand	New Zealand	Both	Yes/No	No	No		Tertiary			Late Cret	54	36	108	144	G
Northern Apennines	Italy	Alpine	Thin	Partial	No	Partial		Miocene	2		Plio-Pleist	30	105	1841	1946	G

Table 1. Continued

Fold belt	Country	Orogen	Thin or thick skinned	Buried	Salt seal	Salt detachment	Salt detachment age	Onset of last deformation	Comp- etent beam (km)	Depth to detach- ment (km)	Source age	No. of belt in Fig. 2	Oil + Cond- ensate (mm bbl)	Gas (mm boe)	Total reserve (mm boe)	Oil or Gas index	Mat- urity Gas index
Northern Rockies FB	Canada	Rockies	Thin	No	No	No		Palaeocene			Cambrian	3	235	29	264	O	
Oman FB	Oman	Zagros	Thick	Yes	No	No		Miocene			Late Precamb	37	6	5	11	O	15
Papuan FB	Papua New Guinea	New Guinea	Both	No	No	No		Miocene	0	5	Jurassic	53	770	2245	3015	G	
Potwar FB	Pakistan	Himalayan	Thin	No	No	Yes	EOCamb	Palaeocene	3	3-5	Palaeocene	40	401	390	791	G	
Pyrenees	France, Spain	Alpine	Thin	No	No	Yes	Trias	Eocene	1	>3	Late Jurassic	26	641	1921	2562	G	
Qilian Shan FB	China	Himalayan	Thick	No	No	No		Jurassic			Early Palaeoz	45	0	22	22	G	
Reforma FB	Mexico	Mexican	Thin	Partial	No	Yes	Callov	Palaeocene	1-4	5-6	Middle Cret	9	50765	10641	61406	O	
Rockies FB	Canada	Rockies	Thin	No	Yes	No		Palaeocene			Early Carb	4	1100	936	2036	G	13
San Bernardo FB	Argentina	Andean	Thick	No	No	No		Miocene	>3	>10	Early Cret	22	4637	984	5621	O	46
Sayan-Tuva FB	Russia	East Siberian	Thick	Yes	Yes	No		Jurassic		>10	Late Precamb	43	267	6540	6807	G	61
Seram FB	Indonesia	Banda Arc	Thick	No	No	No		Miocene			Late Triassic	50	21	1	22	O	
Sierra Madre Orientale	Mexico	Mexican	Thin	No	No	Yes	Trias	Campanian	>5	>5	Late Jurassic	6	2	58	60	G	
Southern Alps	Italy	Alpine	Thin	Yes	Yes	Yes	Trias	Eocene	1-4	>2	Late Triassic	27	29	163	192	G	
Southern Apennines	Italy	Alpine	Thin	Partial	No	Partial		Miocene	2		Late Triassic	31	906	531	1437	O	
Sulaiman FB	Pakistan	Himalayan	Thin	No	No	No		Palaeocene	1	>5	Early Cret	39	32	2819	2852	G	
Taiwan FB	Taiwan	Taiwan	Thin	No	No	No		Pliocene			Unknown	49	50	443	493	G	
Tien Shan FB	China	Himalayan	Thick	Yes/Part	No	No		Oligocene	3-5	>10	Late Permian	42	11214	2576	13789	O	69
Timor FB	East Timor	Banda Arc	Thick	No	No	No		Miocene			Late Triassic	51	0	0	0	O	
Trinidad FB	Trinidad and Tobago	Caribbean	Thin	No	No	No		Pliocene	3	3-5	Late Cret	13	2520	567	3087	O	47
Ucayali FB	Peru	Andean	Thick	No	No	No		Miocene	1	>10	Late Triassic	16	57	64	120	G	
Ural FB	Russia	Urals	Thin	No	Yes	No		Permian	4	4	Late Dev	35	817	2894	3711	G	4
Utah Wyoming FB	USA	Rockies	Thin	No	Yes	No		Palaeocene			Middle Cret	5	600	3167	3767	G	
Veracruz FB	Mexico	Mexican	Thin	Partial	No	Yes		Late Cret	5	5	Late Cret	7	130	242	372	G	
Yunan Guizhou FB	China	Himalayan	Thin	No	Yes	No		Tertiary		>5	Late Triassic	46	0	2820	2820	G	50
Zagros FB	Iran, Iraq, Syria, Turkey	Zagros	Both	Partial	Yes	No/Part		Pliocene	3	8	Middle Cret	36	152170	80338	232508	O	24

FB, fold belt. Stratigraphic ages are abbreviated as necessary; mm boe, million barrels oil equivalent; mm bbl, million barrels.

Table 2. Key fold belt references

Fold belt	References	Fold belt	References
Altun Shan Fold Belt	Gu & Di 1989; Qinmin & Coward 1990; Jin <i>et al.</i> 2002	New Zealand	Knox 1982; Pilaar & Wakefield 1984; Collier & Johnston 1990
Arctic Fold Belt	Harrison & Bally 1988	Northern Apennines	Mattavelli <i>et al.</i> 1993; Zappaterra 1994; Coward <i>et al.</i> 1999
Assam Fold Belt	Bastia <i>et al.</i> 1993; Mallick <i>et al.</i> 1997; Kent <i>et al.</i> 2002	Northern Rockies Fold Belt	Yose <i>et al.</i> 2001
Atlas Fold Belt	Beauchamp <i>et al.</i> 1996, 1999	Oman Fold Belt	Grantham <i>et al.</i> 1987; Robertson <i>et al.</i> 1990; Mount <i>et al.</i> 1998
Balkan Fold Belt	Karaguleva & Cankov 1974; Foose & Mannheim 1975	Papuan Fold Belt	Hill <i>et al.</i> 2004
Banggai Fold Belt	Shaw & Packham 1992	Potwar Fold Belt	Khan <i>et al.</i> 1986; Pennock <i>et al.</i> 1989; Dolan 1990
Beni Fold Belt	Illich <i>et al.</i> 1984; Baby <i>et al.</i> 1995	Pyrenees	Esipalite & Drouet 1992; Bourrouilh <i>et al.</i> 1995; Le Vot <i>et al.</i> 1996
Betic Fold Belt	Blankenship 1992	Qilian Shan Fold Belt	Chen <i>et al.</i> 1987; Guo & Zhang 1989; Ulmishek 1992
Brooks Range	Hubbard <i>et al.</i> 1987; ANWR Assessment Team US Geological Survey 1998; Cole <i>et al.</i> 1998	Reforma Fold Belt	Peterson 1983; Gonzalez-Garcia & Holguin-Quinones 1991; Santiago & Baro 1992
Carpathian Thrust Belt	Roure <i>et al.</i> 1993; Krejci <i>et al.</i> 1996; Slaczka 1996	Rockies Fold Belt	Bally <i>et al.</i> 1966; Cooper 2000; Stockmal <i>et al.</i> 2001
Caucasus Fold Belt	Ulmishek 1990, 2001; Abrams & Narimanov 1997	San Bernardo Fold Belt	Homovc <i>et al.</i> 1995; Peroni <i>et al.</i> 1995
Chaco Fold Belt	Dunn <i>et al.</i> 1995; Moretti <i>et al.</i> 1996	Savan-Tuva Fold Belt	Kontorovich <i>et al.</i> 1990
Cuban Fold Belt	Ball <i>et al.</i> 1985; Echevarria-Rodriguez <i>et al.</i> 1991; Campos <i>et al.</i> 1996	Seram Fold Belt	Courteney <i>et al.</i> 1988; Sykora 2000
Cuyo Fold Belt	Villar & Puettmann 1990; Dellape & Hegedus 1995; Uliana <i>et al.</i> 1995	Sierra Madre Orientale	Gonzalez-Garcia & Holguin-Quinones 1991; Marrett & Aranda 1999; Eguiluz 2001
Dagestan Fold Belt	Sobornov 1994	Southern Alps	Roeder 1992; Anelli <i>et al.</i> 1996
Dinarides	Zappaterra 1994; Velaj <i>et al.</i> 1999	Southern Apennines	Pieri & Mattiavelli 1986; Bally <i>et al.</i> 1988; Zappaterra 1994
Eastern Alps	Muller <i>et al.</i> 1988; Ortner & Sachsenhofer 1996; Zimmer & Wessely 1996	Sulaiman Fold Belt	Raza <i>et al.</i> 1989; Dolan 1990; Jadoon <i>et al.</i> 1994
Eastern Cordillera	Kronman <i>et al.</i> 1995; Reyes <i>et al.</i> 2000	Taiwan Fold Belt	Suppe 1980, 1981
Gissar Fold Belt	Brookfield & Hashmat 1978; Khain <i>et al.</i> 1991	Tien Shan Fold Belt	Wang <i>et al.</i> 1992; Li <i>et al.</i> 1996; Gao & Ye 1997
Guajira Prism	Ruiz <i>et al.</i> 2000	Timor Fold Belt	Charlton <i>et al.</i> 1991; Shaw & Packham 1992
Jura Fold Belt	Laubscher 1962; Mascle 1994	Trinidad Fold Belt	Persad 1985; Rohr 1991; Requejo <i>et al.</i> 1994
Kirthar Fold Belt	Dolan 1990; Robinson <i>et al.</i> 1999; Schelling 1999	Ucayali Fold Belt	Illich <i>et al.</i> 1985; Mathalone & Montoya 1995
Llanos Foothills	Cazier <i>et al.</i> 1995; Cooper <i>et al.</i> 1995; Drozd & Piggott 1996	Ural Fold Belt	Masters & Peterson 1981; Dikenshteyn 1986; Ulmishek 1988
Loei-Phetchabun Fold Belt	Cooper <i>et al.</i> 1989; Sattayarak <i>et al.</i> 1989	Utah Wyoming Fold Belt	Lamerson 1982; Warner 1982
Madre de Dios Fold Belt	Mathalone & Montoya 1995; Moretti <i>et al.</i> 1996	Veracruz Fold Belt	Moran-Zenteno 1994; Jennette <i>et al.</i> 2003
Malargue-Agrio Fold Belt	Mello <i>et al.</i> 1994; Urien & Zambrano 1994; Manceda & Figueroa 1995	Yunan Guizhou Fold Belt	Chen <i>et al.</i> 1994; Ryder <i>et al.</i> 1994
Maturin Fold Belt	Talukdar <i>et al.</i> 1988; Rouré <i>et al.</i> 1994; Parnaud <i>et al.</i> 1995	Zagros Fold Belt	Bordenave & Burwood 1990; Beydoun <i>et al.</i> 1992; Berberian 1995
NE Caribbean Fold Belt	Speed <i>et al.</i> 1991; Babaie <i>et al.</i> 1992; Wallace <i>et al.</i> 2003		

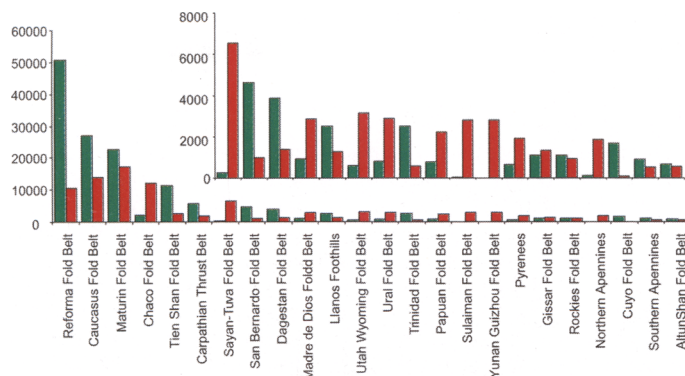


Fig. 3. Graph of the distribution of hydrocarbon reserves in fold and thrust belts, in order of decreasing total reserves. Green, oil and condensate in mm bbl; red, gas in mm boe. The Zagros Fold Belt is excluded from the chart; the inset chart represents the fold belts vertically below at a larger scale.

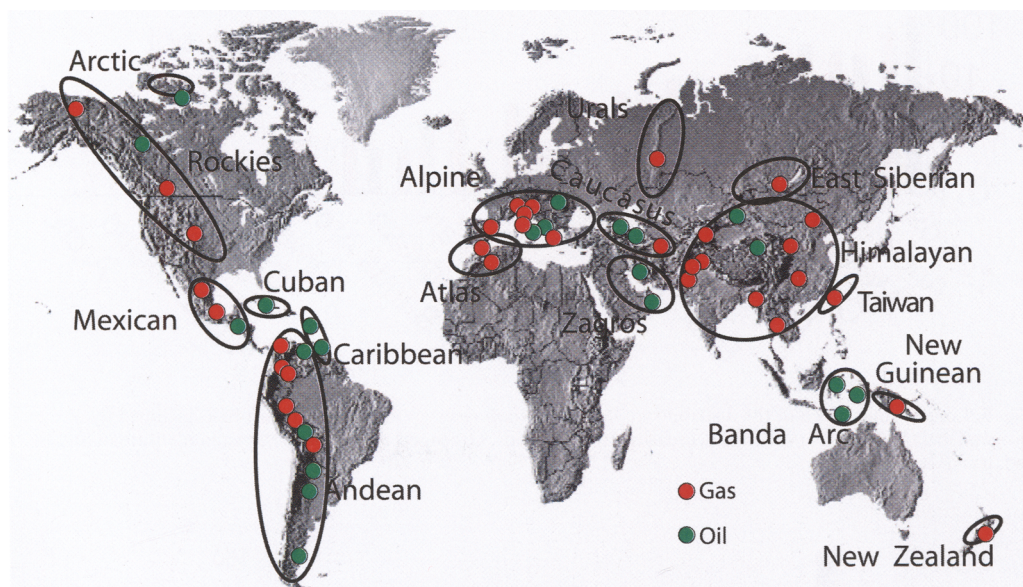


Fig. 4. Location map of orogenic belt groupings for the fold and thrust belts included in this study (Table 1).

by basin and sub-basin but not by fold belt. The dataset had to be carefully reviewed and edited to extract only fields that are within fold belts and to assign each field to the appropriate fold belt. The initial dataset of nearly 22 000 fields was reduced to just over 2900 fields. The key references for the geological attributes of each fold belt are listed in Table 2. In several cases an attribute has been recorded as partial (Table 1), which means that it is present only over a portion of the (sub)basin area. In addition, many of the fold and thrust belts span a number of

(sub)basins that may have different attributes; in such cases the reserves in that (sub)basin have been appropriately attributed and the fold belt noted as having a mixture of characteristic factors (Table 1). Those fold and thrust belts that Mike Coward worked on during his career are highlighted in Figure 2, which illustrates the extent of his influence in shaping the understanding of many of these fold and thrust belts.

The database includes 37 fold and thrust belts that contain giant fields (> 250 million barrels of oil equivalent mm boe); 25 of the fold and thrust

belts have reserves of more than 1 billion barrels of oil equivalent (bn boe) and 16 have reserves of more than 3 bn boe (Fig. 3 and Table 1). The fold belts which lie in the last category include the Zagros Fold Belt (one of the world's most prolific hydrocarbon provinces) the Maturin Basin of East Venezuela, the Reforma Fold Belt in Mexico, the Caucasus and the Tien Shan in China (Fig. 3). The thrust and fold belts with the largest total reserves are mostly dominated by oil, with the notable exception of the Chaco Fold Belt (Fig. 3 and Table 1).

The fold and thrust belts can be conveniently grouped into the orogenic systems within which

they are located (Fig. 4); this allows for the analysis of the established reserves in the orogenic belts. The orogenic belts are ranked by total reserves in Figure 5; the graphs show the split of oil, gas and condensate expressed in billions of barrels (bn bbl) or billions of barrels of oil equivalent for gas (bn boe). The dataset is dominated by the Zagros Fold Belt, which accounts for 49% of all the established reserves in the fold belts around the world and has four times the reserves of the next largest orogenic belt, the Andean Orogen. This strongly skews any observations and conclusions drawn from the analysis of the reserves data and for this reason the

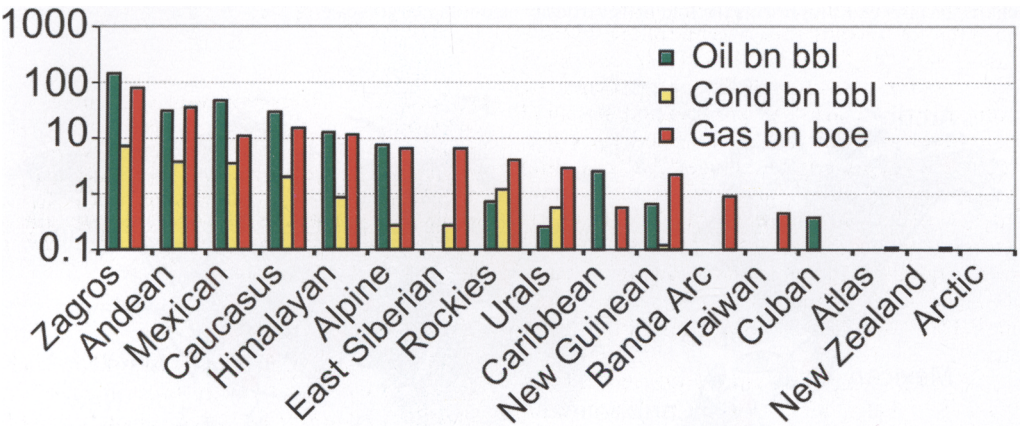


Fig. 5. Logarithmic graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by orogenic belt (Table 1), in order of decreasing total reserves. Green, oil in bn bbls; yellow, condensate in bn bbl; red, gas in bn boe.

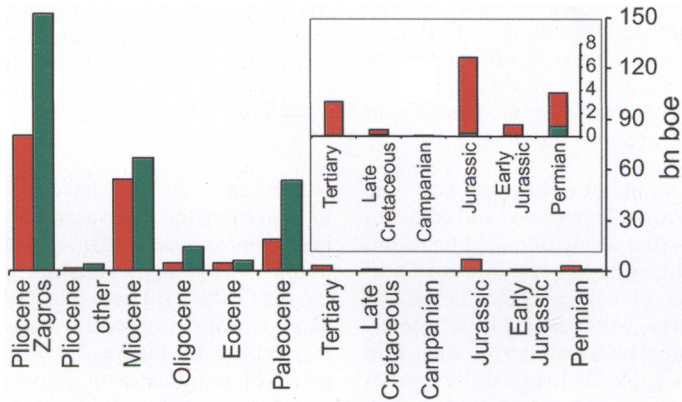


Fig. 6. Graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by the age of onset of the last phase of deformation (Table 1). Green, oil and condensate in bn bbl; red, gas in bn boe. The inset chart shows the older ages of deformation at a larger scale.

Zagros Fold Belt has been isolated on subsequent graphs. Oil is the dominant hydrocarbon type in the six orogenic belts with the largest reserves; the exception is the Andean Orogen, where gas is slightly more significant.

Analysis of fold and thrust belt reserves

Reserves by age of deformation

The reserves can be analysed by the age of the onset of the last phase of deformation in the fold and thrust belt (Fig. 6); any earlier deformation phases are ignored. This shows the Pliocene age deformation of the Zagros Fold Belt to be dominant. The Miocene and Palaeocene are the second and third most important times of hydrocarbon-rich fold and thrust belt development. All other times of fold and thrust belt last phase deformation are volumetrically insignificant by comparison. Clearly the preservation potential of a fold and thrust belt is enhanced when it is relatively young, but as the age of deformation becomes progressively greater, there is more chance of the fold and thrust belt being uplifted and eroded (e.g. the Appalachian fold and thrust belt) or buried to uneconomic depths beneath a later passive margin (e.g. the Variscan fold and thrust belt beneath the European Atlantic margin).

With the exception of the Urals and Sayan-Tuva fold belts, all of the 16 provinces with > 3 bn boe had their last phase of deformation in the Tertiary. The age of the last phase of deformation is important when considering the likelihood of post-charge modification of traps and potential seal failure. It is therefore not surprising that both the Ural and Sayan-Tuva fold belts have salt seals that have helped to maintain trap integrity over lengthy periods of geological time. The inset graph of fold and thrust belts with pre-Tertiary ages of deformation shows that they are strongly gas dominated (Fig. 6). This is not a surprise, as the greater the age of deformation, the more likely it is that the source rock will have entered the gas window as a result of post-orogenic burial.

Source rock age in fold and thrust belts

The age of the primary source rock in each of the fold and thrust belts has also been analysed. Cretaceous source rocks, which also source the Zagros Fold Belt, account for nearly 75% of all fold and thrust belt reserves (Fig. 7). Even with the Zagros Fold Belt excluded, Cretaceous source rocks are still the volumetrically most

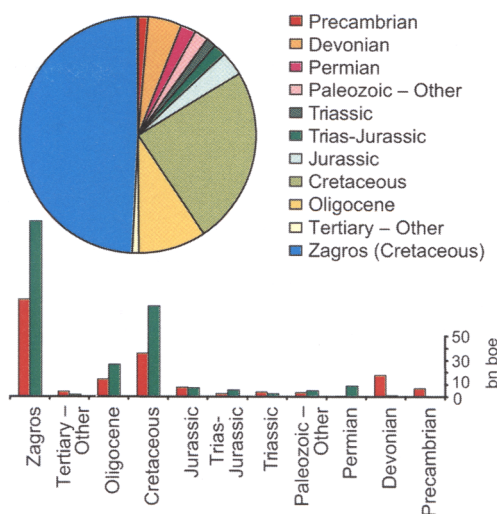


Fig. 7. Graphs of the distribution of hydrocarbon reserves in fold and thrust belts grouped by the age of the source rock (Table 1). The pie chart shows the total reserves for each grouping of source rock age. The other graph shows the distribution of hydrocarbon type for each grouping of source rock age. Green, oil and condensate in bn bbl; red, gas in bn boe.

significant and have an oil:gas ratio of 70:30. The next most significant source rocks are the Oligocene (dominantly oil), the Devonian (primarily gas), the Jurassic (oil:gas ratio 50:50) and the Permian (oil dominant). Not surprisingly, the pre-Mesozoic source rocks tend to have produced more gas than oil reserves, which does not necessarily imply any correlation with the type of source rock. It probably has more to do with the greater likelihood of being more thermally mature as a result of greater burial since deposition. The geographical distribution of source rock ages in fold and thrust belts are shown in Figure 8.

Reserves by deformation style

Deformation style strongly influences the distribution of reserves within fold and thrust belts. The parameters captured in the summary table (Table 1) that influence deformation style include whether the fold and thrust belt is thin or thick skinned, the presence of a salt seal, the presence of a salt detachment and whether the fold and thrust belt is buried or not.

Giant fields are often hosted by simple structures in fold and thrust belts. The key factors in determining the likelihood of their existence

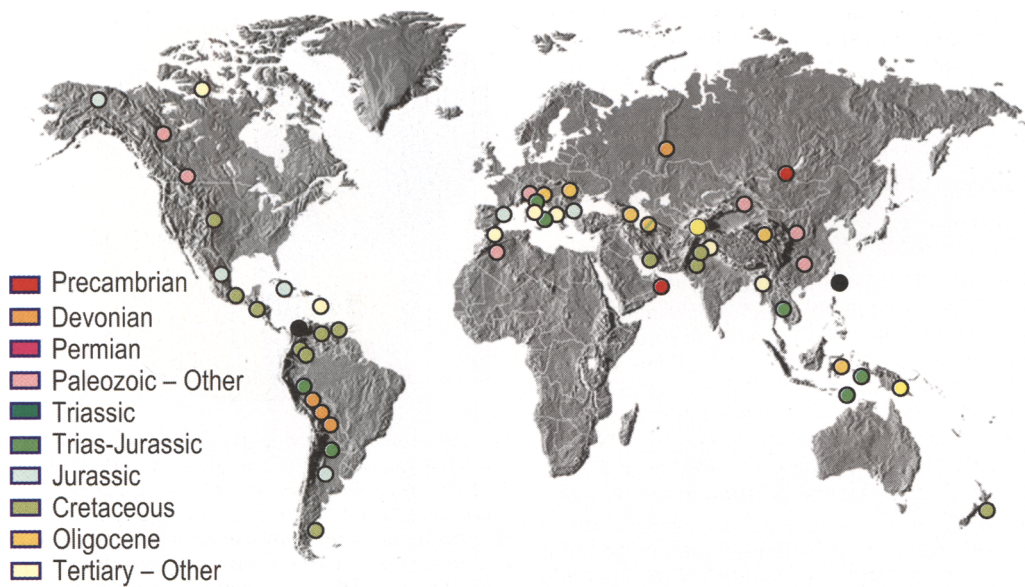


Fig. 8. Map showing the distribution of the age of the source rock in fold and thrust belts reviewed (Table 1). Where more than one age of source rocks is a significant contributor both colours are shown on the symbol as diagonal stripes.

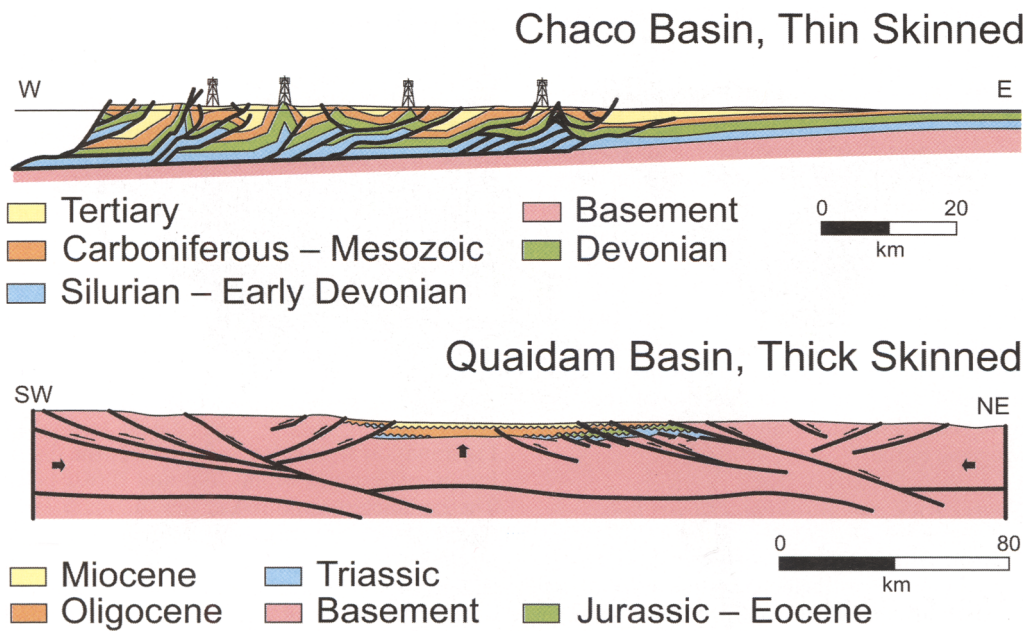


Fig. 9. Cross-sections through examples of thin- and thick-skinned fold and thrust belts to illustrate characteristic geometries. The thin-skinned Chaco Basin section is modified from Moretti *et al.* (1996); the thick-skinned Quaidam Basin section from the Altun Shan fold belt is modified from Qinmin & Coward (1990).

include the presence of a thick competent unit (e.g. >2 km of carbonate) in the hanging wall, thus encouraging simple box folds (e.g. the Zagros Fold Belt), and the depth to detachment for the system. These data have been captured in Table 1 but have not been analysed in detail.

Thin-skinned, thick-skinned or both thin- and thick-skinned. For the analysis of the thin- or thick-skinned style of deformation the dominant style of the productive structures has been considered, as opposed to considering the style of all structures in the fold and thrust belt. The deformation is considered to be thick skinned if it involves a significant thickness of the crust (Coward 1983), which usually implies that the basal detachment is within crystalline basement (Cooper 1996). Figure 9 shows type examples of thin- and thick-skinned deformation in fold and thrust belts.

Thin-skinned deformation accounts for c. 60% of reserves in fold and thrust belts excluding the Zagros Fold Belt (Fig. 10). The Zagros Fold Belt shows both thick- and thin-skinned deformation, based on the recent work of Blanc *et al.* (2003). The thick-skinned fold and thrust belts have a slightly higher oil:gas ratio in comparison with thin-skinned fold and thrust belts, but neither differs significantly from the overall oil:gas ratio in fold and thrust belts (Fig. 1). The

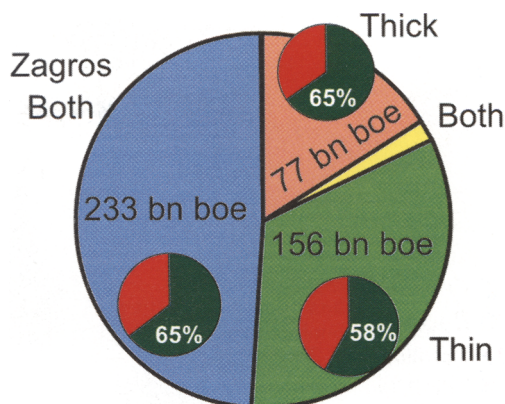


Fig. 10. Graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by thin- or thick-skinned deformation style (Table 1). The pie chart shows the total reserves for each grouping of deformation style; total volumes are labeled on the pie chart segments. The smaller pie charts indicate the proportions of oil and condensate to gas for each deformation style with the percentage of oil and condensate labelled. Green, oil and condensate; red, gas.

geographical distribution of thin-skinned, thick-skinned and mixed fold and thrust belts is shown in Figure 11.

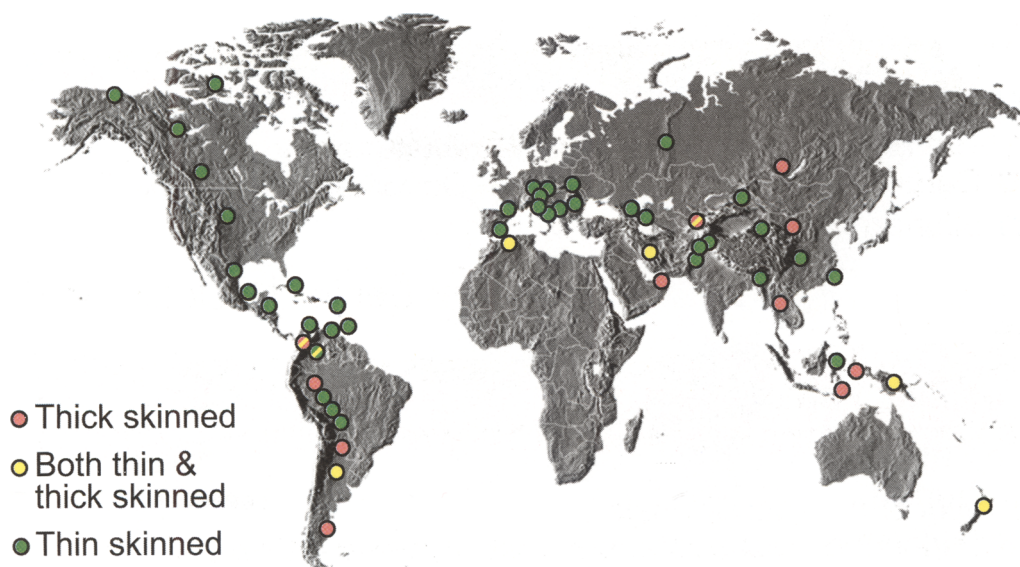


Fig. 11. Map showing the distribution of deformation style in the fold and thrust belts reviewed (Table 1). Where more than one deformation style is present the symbol shows diagonally striped colours representing the two deformation styles.

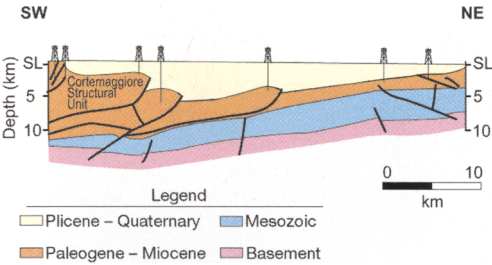


Fig. 12. Cross-section through the Northern Apennines, an example of a buried fold and thrust belt; modified from Pieri (1992).

Burial of fold belts. Another aspect of geometry and deformation history and style that was examined is whether or not the fold and thrust belt has been buried by either syn- or post-depositional sediments, exemplified by the Northern Apennines (Fig. 12). Normally, thrusting is associated with elevation and the simple structures of the frontal zones form last and will post-date the significant loading and hydrocarbon generation. Burial, however, encourages maturation of the source after trap formation if the source was either immature or early mature during the deformation.

Partially buried fold and thrust belts dominate the reserves distribution even when the partially buried Zagros Fold Belt is excluded

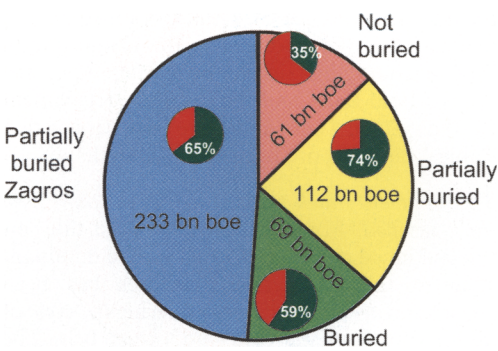


Fig. 13. Graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by burial state (Table 1). The pie chart shows the total reserves for each grouping of burial state; total volumes are labeled on the pie chart segments. The smaller pie charts indicate the proportions of oil and condensate to gas for each burial state with the percentage of oil and condensate labelled. Green, oil and condensate; red, gas.

from consideration (Fig. 13). Oil is the most important hydrocarbon type in partially buried fold and thrust belts (Fig. 3). Fold and thrust belts, that are buried, are strongly dominated by oil, and those that are not buried are dominated by gas (Fig. 13). The geographical distribution of the different classes of burial by sediment in fold and thrust belts is shown in Figure 14.

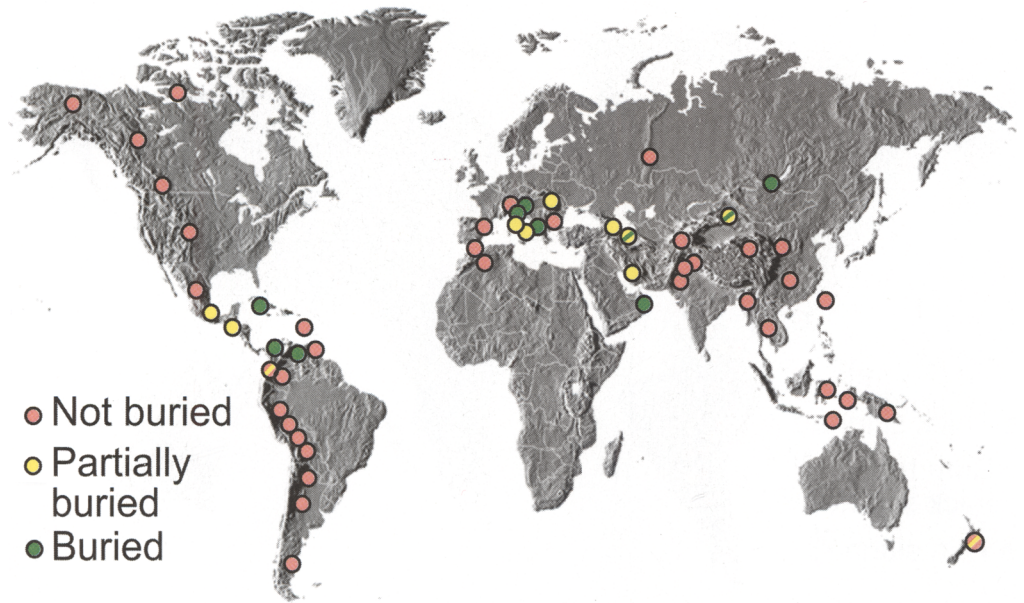


Fig. 14. Map showing the distribution of burial state in the fold and thrust belts reviewed (Table 1). Where more than one burial state is present the symbol shows diagonally striped colours representing the two burial states.

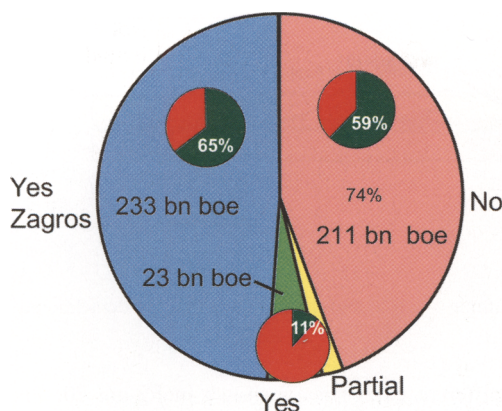


Fig. 15. Graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by presence of salt seal (Table 1). The pie chart shows the total reserves for each grouping of seal type; total volumes are labelled on the pie chart segments. The smaller pie charts indicate the proportions of oil and condensate to gas for each seal type with the percentage of oil and condensate labelled. Green, oil and condensate; red, gas.

Salt Seals in fold and thrust belts. The presence of a salt top seal in fold and thrust belts is not significant in the reserves distribution, with the notable exception of the Zagros Fold Belt, which is oil dominant (Fig. 15). The other fold and

thrust belts that have salt top seals are very strongly gas-prone, which is possibly due to the effectiveness of the salt seal in retaining a gas charge, and the majority have a Palaeogene or earlier final phase of deformation. In fold and thrust belts with no salt seal, oil is the dominant hydrocarbon type (Fig. 15). The geographical distribution of salt seals in fold and thrust belts is shown in Figure 16.

Salt detachments in fold and thrust belts. The presence of a salt detachment in a fold and thrust belt has a strong influence on the deformation style, tending to favour thin-skinned structures as a result of the efficiency of the detachment (Fig. 17). The Zagros Fold Belt is problematic in this analysis, as a recent paper (Blanc *et al.* 2003) suggested that the Vendian–Cambrian Hormuz Salt is present only in the SE part of the Zagros Fold Belt, which is less petroliferous (Fig. 18). Fold and thrust belts with no salt detachment dominate the reserves, excluding the Zagros Fold Belt; in fold and thrust belts with no salt detachment the oil:gas ratio is *c.* 50:50, in contrast to fold and thrust belts with a salt detachment, where the oil:gas ratio is about 80:20 (Fig. 18). This could perhaps be due to the salt detachment inhibiting the migration of gas from secondary deeper and more mature source rock horizons beneath the salt detachment into the traps located above the detachment. The geographical

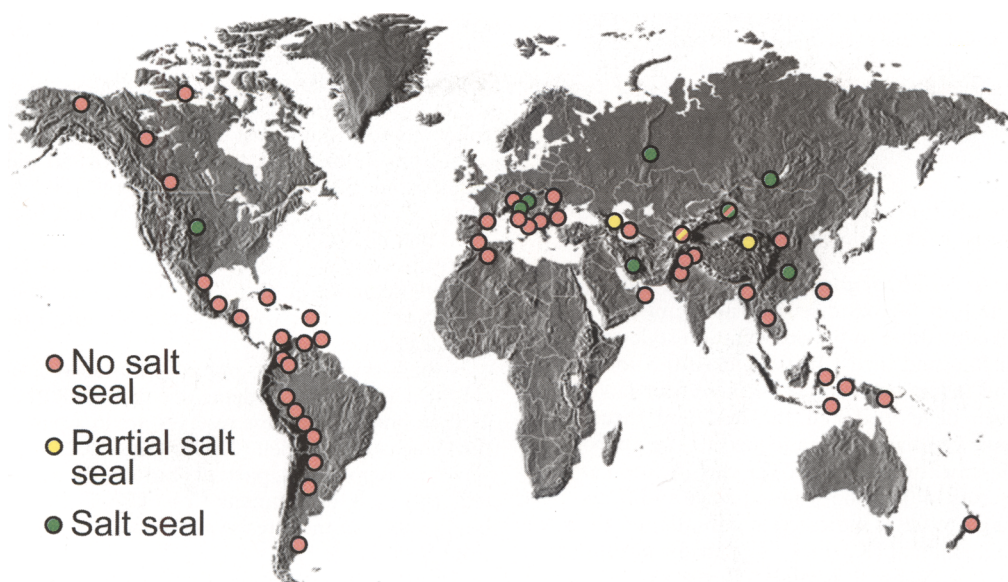


Fig. 16. Map showing the distribution of seal type in the fold and thrust belts reviewed (Table 1). Where more than one seal type is present the symbol shows diagonally striped colours representing the two seal types.

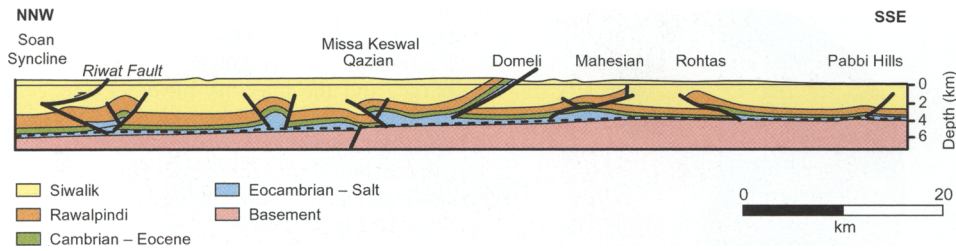


Fig. 17. Cross-section through the Potwar Fold Belt, an example of a fold and thrust belt with a salt detachment; modified from Pennock *et al.* (1989).

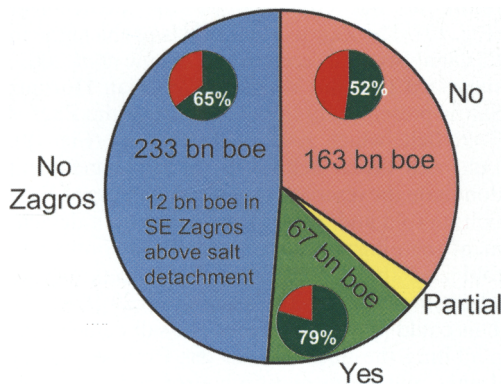


Fig. 18. Graph of the distribution of hydrocarbon reserves in fold and thrust belts grouped by presence of salt detachment (Table 1). The pie chart shows the total reserves for each grouping of detachment type; total volumes are labelled on the pie chart segments. The smaller pie charts indicate the proportions of oil and condensate to gas for each detachment type with the percentage of oil and condensate labelled. Green, oil and condensate; red, gas.

distribution of salt detachments in fold and thrust belts is shown in Figure 19.

Reserves distribution based on deformation style. The four factors discussed above in this section all contribute to the deformation styles observed in fold and thrust belts. A classification of fold and thrust belts based on these four factors has been developed and the fold and thrust belts reviewed have been assigned to the appropriate classification category. The classification uses the factors in the following sequence and coded by a single letter as indicated in parentheses, thick- or thin-skinned (K, thick; T, thin; B, both), burial (Y, yes; N, no; P, partial), salt seal (Y, yes; N, no; P, partial) and salt detachment (Y, yes; N, no; P, partial). The reserves distribution is shown in Table 3 and geographical distribution of the

different categories is shown in Figure 20. The Zagros Fold Belt is dominated by oil and is both thick- and thin-skinned, partially buried, has a salt seal and no salt detachment and thus has the classification code of BPYN.

Other categories that favour significant oil reserves are fold and thrust belts that are:

- thin-skinned (T), partially buried (P), no salt seal (N), salt detachment (Y) (TPNY 50.9 bn bbls); >99% of these reserves are in the Reforma Fold Belt (Table 1);

- thin-skinned (T), buried (Y), no salt seal (N), no salt detachment (N) (TYNN 22.6 bn bbls); >99% of these reserves are in the Maturin Fold Belt (Table 1);

- thick-skinned (K), partially buried (P), no salt seal (N), no salt detachment (N) (KPNN 18.8 bn bbls); all of these reserves are in a part of the Caucasus Fold Belt (Tables 1 and 3);

- thick-skinned (K), buried (Y), no salt seal (N), no salt detachment (N) (KYNN 17.2 bn bbls); reserves are in parts of the Caucasus and Tien Shan Fold Belts (Tables 1 and 3).

Significant gas reserves are found in the following fold and thrust belt types:

- thin-skinned (T), unburied (N), no salt seal (N), no salt detachment (N) (TNNN 20.5 bn boe); >60% of these reserves are in the Chaco Fold Belt (Table 1);

- thin-skinned (T), buried (Y), no salt seal (N), no salt detachment (N) (TYNN 17.4 bn boe); >99% of these reserves are in the Maturin Fold Belt (Table 1);

- thick-skinned (K), partially buried (P), no salt seal (N), no salt detachment (N) (KPNN 11.0 bn boe); all of these reserves are in a part of the Caucasus Fold Belt (Tables 1 and 3);

- thin-skinned (T), partially buried (P), no salt seal (N), salt detachment (Y) (TPNY 10.9 bn boe); >99% of these reserves are in the Reforma Fold Belt (Table 1).

Clearly, the categories that favour large oil reserves also favour large gas reserves and in terms of total reserves the top four categories excluding the Zagros Fold Belt are as follows.

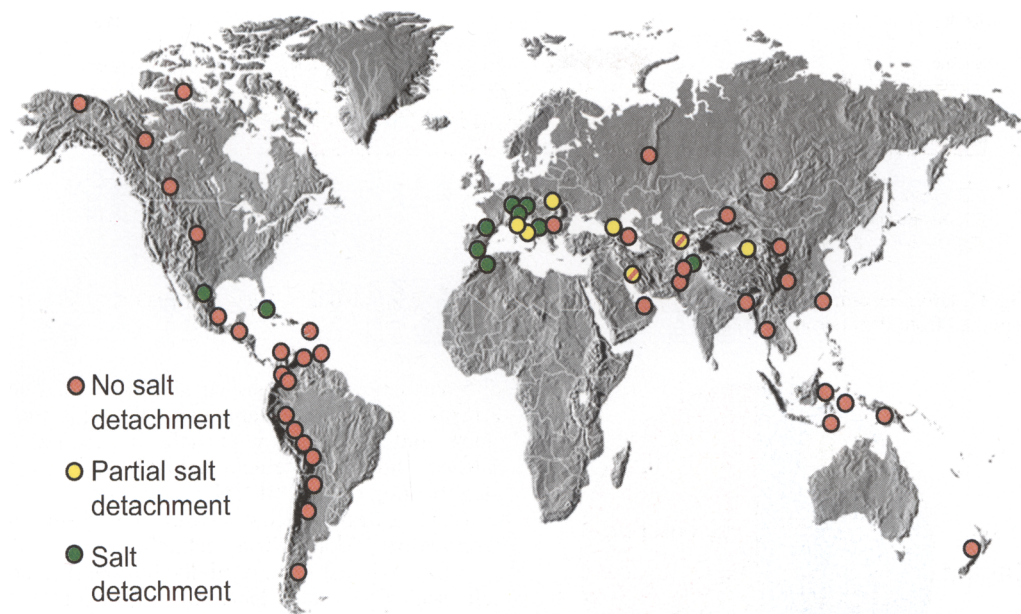


Fig. 19. Map showing the distribution of detachment type in the fold and thrust belts reviewed (Table 1). Where more than one detachment type is present the symbol shows diagonally striped colours representing the two detachment types.

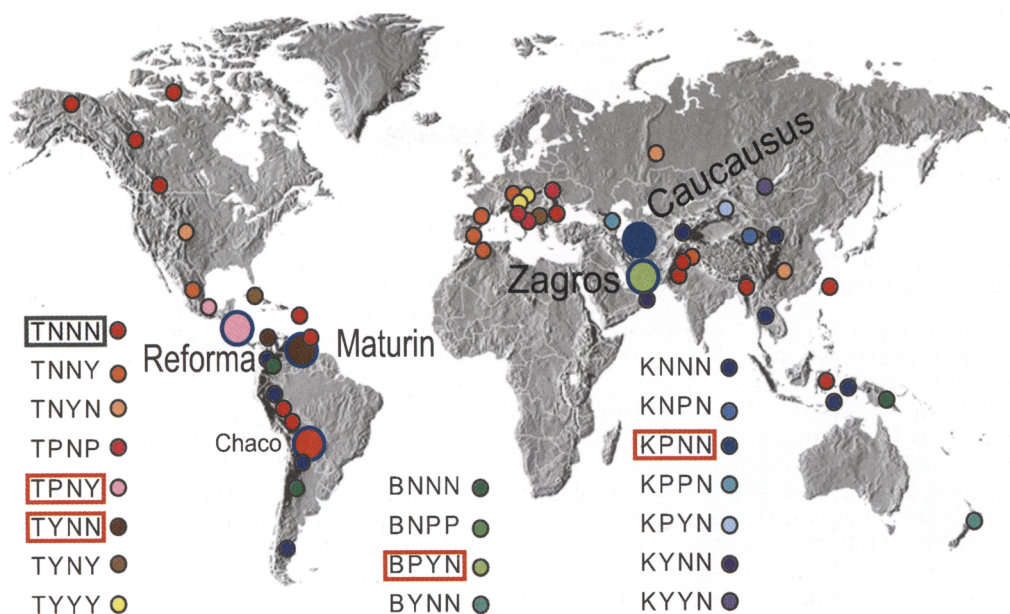


Fig. 20. Map showing the distribution of deformation style in the fold and thrust belts reviewed (Table 3). Where more than one deformation style is present the symbol shows only the colour of the predominant deformation style.

Table 3. *Classification of deformation style*

Thick or thin skinned	Burial	Salt seal	Salt detachment	Fold belts	Type code	Oil & condensate recoverable (mm bbl)	Gas recoverable (mm boe)
Thick & thin skinned	Unburied	No salt seal	No salt detachment	Llanos (part), Malargue-Agrio, Papuan, New Zealand (part)	BNNN	3763	3802
Thick & thin skinned	Unburied	No salt seal	Salt detachment	Atlas	BNNY	94	107
Thick & thin skinned	Unburied	Partial salt seal	Partial salt detachment	Gissar (part)	BNPP	244	1072
Thick & thin skinned	Partially buried	Salt seal	No salt detachment	Zagros	BPYN	152170	80338
Thick & thin skinned	Buried	No salt seal	No salt detachment	New Zealand (part)	BYNN	36	68
Thick skinned	Unburied	No salt seal	No salt detachment	Cuyo, E Cordillera (part), San Bernado, Ucayali, Seram, Timor, Gissar (part), Loei Phetchabun, Qilian Shan	KNNN	7263	1606
Thick skinned	Unburied	Partial salt seal	No salt detachment	Altun Shan	KNPN	664	554
Thick skinned	Partially buried	No salt seal	No salt detachment	Caucasus (part)	KPNN	18821	11002
Thick skinned	Partially buried	Partial salt seal	No salt detachment	Dagestan	KPPN	3897	1386
Thick skinned	Partially buried	Salt seal	No salt detachment	Tien Shan (part)	KPYN	2104	1995
Thick skinned	Buried	No salt seal	No salt detachment	Caucasus (part), Tien Shan (part), Oman	KYNN	17249	3556
Thick skinned	Buried	Salt seal	No salt detachment	Sayan-Tuva	KYYN	267	6540
Thin skinned	Unburied	No salt seal	No salt detachment	Balkan, Beni, Chaco, Madre de Dios, Llanos (part), Arctic, Banggai, NE Caribbean, Trinidad, Assam, Kirthar, Sulaiman, N Rockies, Rockies (Can), Taiwan	TNNN	5998	20532
Thin skinned	Unburied	No salt seal	Salt detachment	Betic, Jura, Pyrenees, Potwar, Sierra Madre Orientale	TNNY	1044	2374
Thin skinned	Unburied	Salt seal	No salt detachment	Yunan Guizhou, Utah-Wyoming, Urals	TNYN	2517	9614
Thin skinned	Partially buried	No salt seal	Partial salt detachment	Carpathians, N Apennines, S Apennines	TPNP	6653	4158
Thin skinned	Partially buried	No salt seal	Salt detachment	Reforma, Veracruz	TPNY	50895	10883
Thin skinned	Buried	No salt seal	No salt detachment	Guajira, Maturin, E Cordillera (part)	TYNN	22612	17445
Thin skinned	Buried	No salt seal	Salt detachment	Dinarides, Hellenides, Cuban	TYNY	970	238
Thin skinned	Buried	Salt seal	Salt detachment	E Alps, S Alps	TYYY	35	203

- thin-skinned (T), partially buried (P), no salt seal (N), salt detachment (Y) (TPNY 61.8 bn boe); >99% of these reserves are in the Reforma Fold belt (Table 1);

- thin-skinned (T), buried (Y), no salt seal (N), no salt detachment (N) (TYNN 40.1 bn boe); >99% of these reserves are in the Maturin Fold Belt (Table 1). It should be noted that this deformation style would also include the fold and thrust belts that develop as the contractional toes to extensional systems on continental margins. These fold belts have become important hydrocarbon provinces (e.g. the deep-water Gulf of Mexico, deep-water Niger Delta and Brazil), but were excluded from this review as discussed above.

- thin-skinned (T), unburied (N), no salt seal (N), no salt detachment (N) (TNNN 30.3 bn boe); 47% of these reserves are in the Chaco Fold Belt (Table 1).

- thick-skinned (K), partially buried (P), no salt seal (N), no salt detachment (N) (KPN 29.8 bn boe); all of these reserves are in a part of the Caucasus Fold Belt (Tables 1 and 3).

This provides some insights into the types of fold and thrust belt that should be explored if significant reserves or a particular hydrocarbon type are desired. One constant factor is that, except for the Zagros Fold Belt, a salt seal does not appear to be necessary for significant reserves to be present. What is particularly striking is that in most of the categories discussed above, there is one fold and thrust belt that dominates the reserves in the category. The only exception is the TNNN category, where, although the Chaco Fold Belt accounts for a high proportion of the reserves, a number of other fold belts also contribute significant reserves (Table 3). The data suggest that, based on deformation style, prolific hydrocarbons occur in fold belts that are thin-skinned with no salt detachment or salt seal. Whether or not the thin-skinned fold and thrust belt is buried does not appear to be a critical factor.

A key observation from this analysis is that the six most richly endowed fold and thrust belts have no common set of deformation style attributes. The conclusion is that deformation style attributes are not critical factors in controlling the hydrocarbon endowment of fold and thrust belts and that the non-structural elements of the petroleum system are more important in determining hydrocarbon endowment.

Gas- and oil-prone thrust belts

The characteristics of gas- or oil-prone fold and thrust belts are based on total gas and oil reserves

rather than the number of fold and thrust belts dominated by each hydrocarbon type. Whether a fold and thrust belt is thin- or thick-skinned does not appear to be a critical factor in determining the dominant hydrocarbon type; however, the other factors described above definitely are.

- Gas-prone fold and thrust belts are characterized by a pre-Palaeogene age of the last deformation phase, Palaeozoic source rocks, a salt seal, no salt detachment and are not at present buried by syn- or post-orogenic sediment.

- Oil-prone fold and thrust belts are characterized by a Cenozoic age of the last deformation phase, post-Jurassic source rocks; no salt seal (excepting the Zagros Fold Belt), a salt detachment and are currently buried or partially buried by syn- or post-orogenic sediment.

This very clear distinction provides a potential tool for the exploration of fold and thrust belts where a particular hydrocarbon type is the goal of the exploration programme. In the author's opinion the most important factor is the age of the last deformation.

Exploring petroleum systems in fold and thrust belts

The area of a fold and thrust belt that is most prospective for hydrocarbons is the external foothills belt between the leading thrust of the internal zone and the limit of thrusting in the foreland basin, whether emergent or buried. Commercial quantities of oil and gas have been discovered in almost 50 fold and thrust belts (Table 1). Predictably, fields are aligned parallel to the structural trend. Structural traps are usually present throughout the belt, yet hydrocarbon reserves tend to be located in a fairly discrete zone within the thrust belt. In many cases the productive region is a band along the external fringe of the thrust belt. This is because normally the generation and expulsion front moves ahead of the deformation front and the normal asymmetry of the basin encourages migration into the foreland. As a result, there is a stronger possibility of the frontal thrust creating a giant field (>250 mm boe) than for structures that are further back from the thrust front.

Toward the hinterland (internal region of the orogenic belt), the reservoir horizons tend to be breached and flushed, older source rocks may be overmature, and younger source rocks, present in the clastic foredeep, may be absent. Toward the foreland (external region of the orogenic belt) of the productive trend, the reservoir horizons tend to be depositionally thinner, the source

rocks may be immature, the young source rocks may overlie the reservoir, and the structural traps may be small or absent.

Thrust belts have long been considered difficult areas in which to explore for hydrocarbons. One of the reasons for this view is the difficulty of predicting subsurface structure. However, the key risk in many fold and thrust belts is whether trap formation predated hydrocarbon generation. Many of the hydrocarbons generated end up in the foreland in stratigraphic traps, in tar belts and within old structures buried beneath the foreland basin sediments. This problem is summarized below.

- Thrust systems elevate rocks above their regional elevation, thus potentially removing the source rocks from the generating window (A in Fig. 21).

- If the source is intra-thrust sheet then only at the trailing edges will the source be still at regional elevation and capable of generating hydrocarbons. The available fetch will depend on thrust sheet size and will be degraded as displacement increases because less source volume will still be at regional elevation (B and B' in Fig. 21).

- If the source is in the roof sequence the same problems as for intra-horse sourcing apply and communication with the reservoir may be difficult to achieve (C in Fig. 21).

- If the source is in the footwall similar problems apply but in addition migration pathways will be limited by the availability of across-fault juxtapositions of reservoir and source (D in Fig. 21).

- The system will work if subsequent burial of the thrust belt, by syn-orogenic sediments, puts the entire system, including source and traps, in the maturity window. In this case, traps predate the generation and migration of hydrocarbons.

- The system will work if the thrusting is synchronous with, or shortly post-dated rapid burial by, foreland basin sediment. The loading effect of the thrust belt creates the accommodation space in the foreland basin, which is then progressively cannibalized by the prograding thrust system. In this case, the structures develop as the source rocks are in the maturity window; much of the early charge may migrate into the foreland basin but the later charge is trapped.

- The system will work if the thrusting is responsible for pushing the source into the generation window (E in Fig. 21).

Despite having potential source and reservoir rocks several of the fold and thrust belts included in this review have only modest resource endowments (Table 1), probably because of problems with the timing of maturation and structuration. The really prolific fold and thrust belts, with >10 bn boe of reserves (Zagros, Reforma, Maturin, Caucasus, Chaco and Tien Shan), all have world-class source rocks. A good rule of thumb is that one discovery in a particular structural zone of a fold and thrust belt mitigates the primary risk, timing of maturation and migration in relation to trap formation, and normally there will be a number of other accumulations.

Future potential in fold and thrust belts

To assess the future potential of fold and thrust belts, the data in the USGS 2000 World Petroleum Assessment were used (USGS 2000). Unfortunately, this assessment covers only selected hydrocarbon provinces and thus does not provide a complete dataset of yet-to-find (YTF) resource estimates. For those fold and thrust belts where an assessment did exist, a maturity index was calculated, which is the

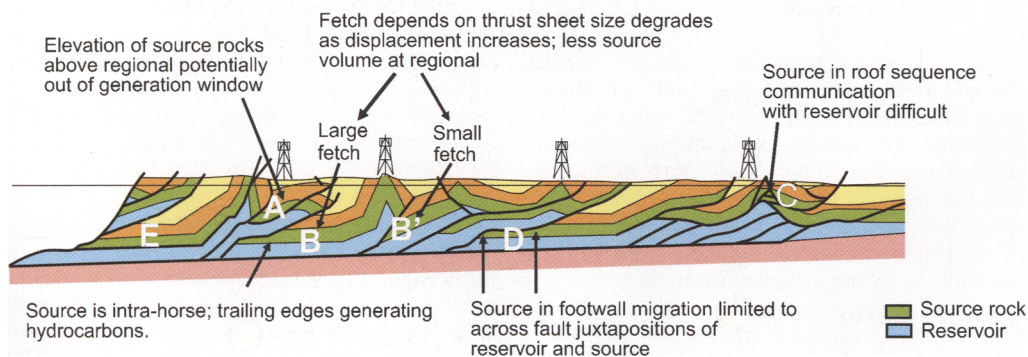


Fig. 21. Cross-section based on Figure 9 annotated to illustrate different configurations of structural geometry and source rock position (see text for discussion).

YTF % of the sum of the discovered reserves and the YTF; the higher this number is the less mature the exploration of the fold and thrust belt (Table 1). All fold and thrust belts that have a yet-to-find resource estimate of > 2 bn boe were compiled into Table 4. Two fold and thrust belts were added to Table 4 for which no YTF numbers were available from the USGS but which are believed to offer significant additional resource potential. The location of the fold and thrust belts is shown on the world map (Fig. 22). Many of the thrust belts in Table 4 remain relatively poorly explored for a number of reasons that include remote location (Gissar, Tien Shan) and limited or lack of access for international oil companies (Zagros, Reforma).

The advent of technology that allows production in ultra-deep water over the last 20 years has driven exploration of the fold and thrust belts that develop as the contractional toes of extensional systems on passive margins (Rowan *et al.* 2004). Some of these systems host significant reserves; for example, the Gulf of Mexico fold belts, the toe of the Niger Delta and deep-water Brazil. These and other similar areas still offer significant undiscovered resource potential.

Conclusions

This paper presents a statistical summary of reserves in fold and thrust belts based primarily

on an IHS dataset of reserves for discovered fields to which a number of geological attributes have been added (Table 1). This provides a powerful summary dataset of the key geological characteristics of the fold belts included in the review, which has been used to interrogate the IHS dataset. The analysis of the data has identified which of the world's fold and thrust belts are the most prolific hydrocarbon provinces and the attributes of these provinces. The most prolific fold and thrust belt is the Zagros Fold Belt, which accounts for 49% of all reserves in fold and thrust belts, and the Zagros Fold Belt has, as a result, been isolated during the analysis to avoid skewing the other conclusions.

Fold and thrust belts represent an average sample of the world's hydrocarbon resources and have a virtually identical oil:gas:condensate ratio to the global resource endowment. Fold and thrust belts are oil prone (59% oil) because they are an almost perfect representation of an oil-prone world. Excluding the Zagros Fold Belt, most of the reserves are contained in fold and thrust belts that are thin-skinned, have no salt detachment or salt seal, are partially buried by syn- or post-orogenic sediments, are sourced by Cretaceous source rocks and underwent the last phase of deformation during the Tertiary. The particularly telling observation, however, is that the top six most richly endowed fold and thrust belts have no common set of structural

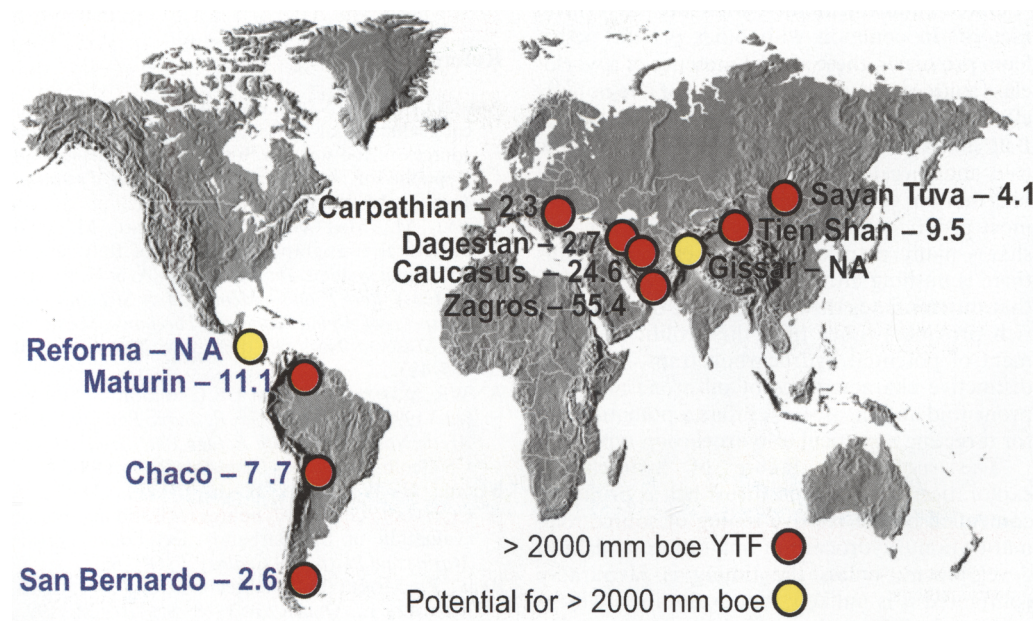


Fig. 22. Map of fold and thrust belts that offer > 2000 mm boe of yet-to-find (YTF) resources (Table 4). NA, not applicable.

Table 4. *Future potential of fold and thrust belts*

Fold belt	Oil + condensate (mm bbl)	Gas (mm boe)	Total (mm boe)	Oil or gas	Maturity index	YTF (mm boe)
Zagros Fold Belt	152170	80338	232508	O	24	55452
Caucasus Fold Belt	26954	13973	40927	O	60	24578
Maturin Fold Belt	22612	17370	39982	O	28	11084
Tien Shan Fold Belt	11214	2576	13789	O	69	9484
Chaco Fold Belt	2033	12034	14067	G	55	7669
Sayan-Tuva Fold Belt	267	6540	6807	G	61	4138
Dagestan Fold Belt	3897	1386	5283	O	51	2717
San Bernardo Fold Belt	4637	984	5621	O	46	2577
Carpathian Thrust Belt	5643	1785	7428	O	31	2280
Gissar Fold Belt	1113	1347	2459	G	n.a.	n.a.
Reforma Fold Belt	50765	10641	61406	O	n.a.	n.a.

YTF, yet-to-find; n.a., not applicable.

attributes. The top six also fall into an attribute set that may also be shared with other fold and thrust belts but within which they dominate, making up >90% of the reserves within the attribute set. This implies that the resource-rich fold and thrust belts all have a unique combination of characteristics that is not necessarily repeatable in others. This also implies that structural attributes are not the critical factor controlling the distribution of hydrocarbon reserves in fold and thrust belts. If the structural attributes of fold and thrust belts are not critical factors in resource endowment then what are the critical factors? In common with other prolific petroleum provinces, these are the presence of a world-class source rock and the presence of a regionally effective reservoir–seal couplet. The Zagros Fold Belt illustrates this perfectly; the most prolific fold and thrust belt is essentially the deformed NE margin of the Arabian Basin, the world's most prolific petroleum province, with which it shares many petroleum system elements. Thus there is nothing intrinsic in fold and thrust belts that differentiates them from other oil- and gas-rich provinces other than the prolific development of potential hydrocarbon traps. The very distinctive characteristics of oil-prone and gas-prone fold and thrust belts offers a potential tool for targeting a particular hydrocarbon type.

The success or failure of hydrocarbon exploration in a fold and thrust belt is primarily controlled by the relative timing of source rock maturation, hydrocarbon migration and trap development; unless the timing is favourably configured it is unlikely that exploration will be successful. The analysis of the maturity index shows that many of the prolific fold and thrust belts still have significant remaining upside;

remote location and politically challenging access have limited opportunities for this potential to be realized.

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