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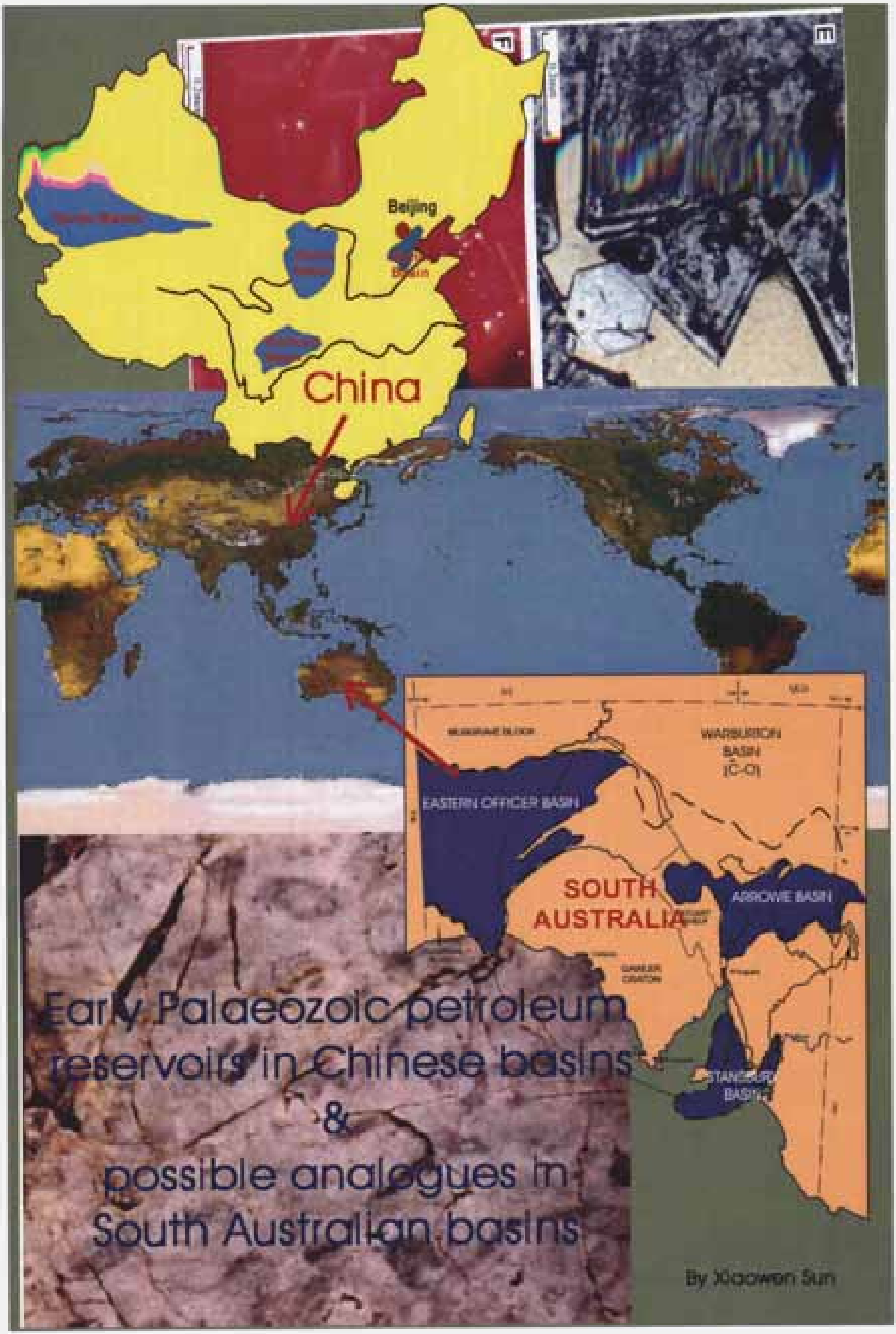
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Early Palaeozoic petroleum reservoirs in Chinese basins & possible analogues in South Australian basins
By Xiaowen Sun

Early Palaeozoic petroleum reservoirs in Chinese basins and possible analogues in South Australian basins

Presented
to

the Petroleum Group

PIRSA

by

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EXECUTIVE SUMMARY

Chinese Cambro-Ordovician sequences, particularly from the Tarim, Ordos, Bohai Gulf and Sichuan Basins contain important petroleum reservoirs and are relatively well studied. Five types of structurally related reservoirs are modelled in these basins; most reservoirs are close stratigraphically to the unconformity between the pre or middle Ordovician and younger Late Palaeozoic, Mesozoic and Cainozoic sequences. The source rocks of these basins are either Cambro-Ordovician or younger overlying sequences and have complex generating histories. Of four basins, especially the Tarim Basin, carbonate petroleum reservoirs are deeply buried, normally between 5000-6000m below the surface, mostly producing gas rather than oil. Four trap types are recognised in the Early Palaeozoic sequences of the Chinese basins: 1) anticlinal structures; 2) palaeohigh structures with overmature or re-migrated gas; 3) palaeohighs or in non-structural strata; 4) palaeokarst (buried hill) traps often by well developed porosity and permeability.

Cambro-Ordovician carbonate sequences are well developed in the Warburton, Officer, Stansbury and Arrowie Basins in South Australia. Economic petroleum flows have been reported only from the Warburton Basin, while some oil bleeds have been reported from several shallow drillholes in the Officer and Arrowie Basins. These Australian basins are similar to Early Palaeozoic sequences of the Chinese basins in terms of stratigraphy, sedimentology, structural style and reservoir quality. Hence, there may be potential for further exploration, particularly in unexplored deeper parts of the South Australian basins. The recent discovery of an unconventional carbonate reservoir in Challum 19 (Warburton Basin) is encouraging for exploration of deeply buried Cambro-Ordovician carbonate sequences. The analogy with Chinese basins indicates that the South Australian basins need more aggressive exploration.

INTRODUCTION

Comparison between different basins can help identify unconventional resources. Moore et al. (1986) compared depositional systems, sedimentation rates, palaeobathymetry and lacustrine source deposits, palaeoclimate and organic geochemistry of the Ordos and Northern Jiangsu Basins of China and the Surat and Eromanga Basins, which widened the search for new targets in those basins. Few Cambro-Ordovician basins in Australia are petroleum productive;

one of them is the Amadeus Basin, which produces gas from Cambro-Ordovician sandstone reservoirs, in comparison with at least four major petroleum productive Cambro-Ordovician basins in China, mostly in carbonate reservoirs.

Apart from the onshore Canning Basin and Woodada Gas Field in the Perth Basin, there are hardly any significant carbonate reservoirs in Australia. The Woodada Gas Field contains a Permian carbonate unit that flowed gas at a rate of 7 million cubic feet per day (MMCFD) from Woodada 1, which is an unconventional and unprecedented carbonate reservoir, called "Carynginia Limestone". It is up to 130m thick, in which the source is oil-prone sections of the Kockatea shale and the gas is likely to have come from the Carynginia Formation and the underlying Irwin River Coal Measures (Couper, 1983; Lane & Watson, 1985). Santos reported on 1st February 2001 that Challum 19 flowed gas at 212,380 cubic metres per day (7.5 MMCFD) through a 13mm (0.5") surface choke from a Pre-Permian carbonate reservoir over the interval 2339m-2367m. This is the first economic discovery in carbonate rock of the Warburton Basin. This discovery of gas from Pre-Permian (Warburton Basin) carbonates opens up a play concept for the Challum Field in the Warburton Basin, Queensland (Santos news release, 2001). Although no carbonate reservoirs have been discovered in South Australia, gas shows and oil bleeding are frequently reported in carbonate rocks of the Officer, Georgina, Arrowie and Warburton Basins (Fig. 1).

In contrast, about 50% of world petroleum production is from carbonate reservoirs. Carbonate reservoirs are very common and productive in many Chinese basins such as the Bohai Gulf (Renqiu oil field), Sichuan (Weiyuan Gas Field), Ordos and Tarim Basins. The Chinese analogues are particularly relevant to further exploring hydrocarbon potential in South Australia since Cambro-Ordovician sequences and karsted vuggy dolomite are common in South Australian Early Palaeozoic basins. This report aims to compare the Tarim, Ordos, Bohai Gulf and Sichuan Basins in China with main South Australian basins, particularly the Warburton Basin, which was well studied in recent years (Gatehouse, 1986; Roberts et al., 1990; Gravestock, 1995; Sun, 1996, 1997a, b, 1998, 1999, 2001; Sun & Gravestock, 2001). The stratigraphy, tectonic history, characteristics of reservoirs, source rocks and seals, structural style and traps of selected Chinese basins are briefly described, in comparison with South Australian frontier basins.

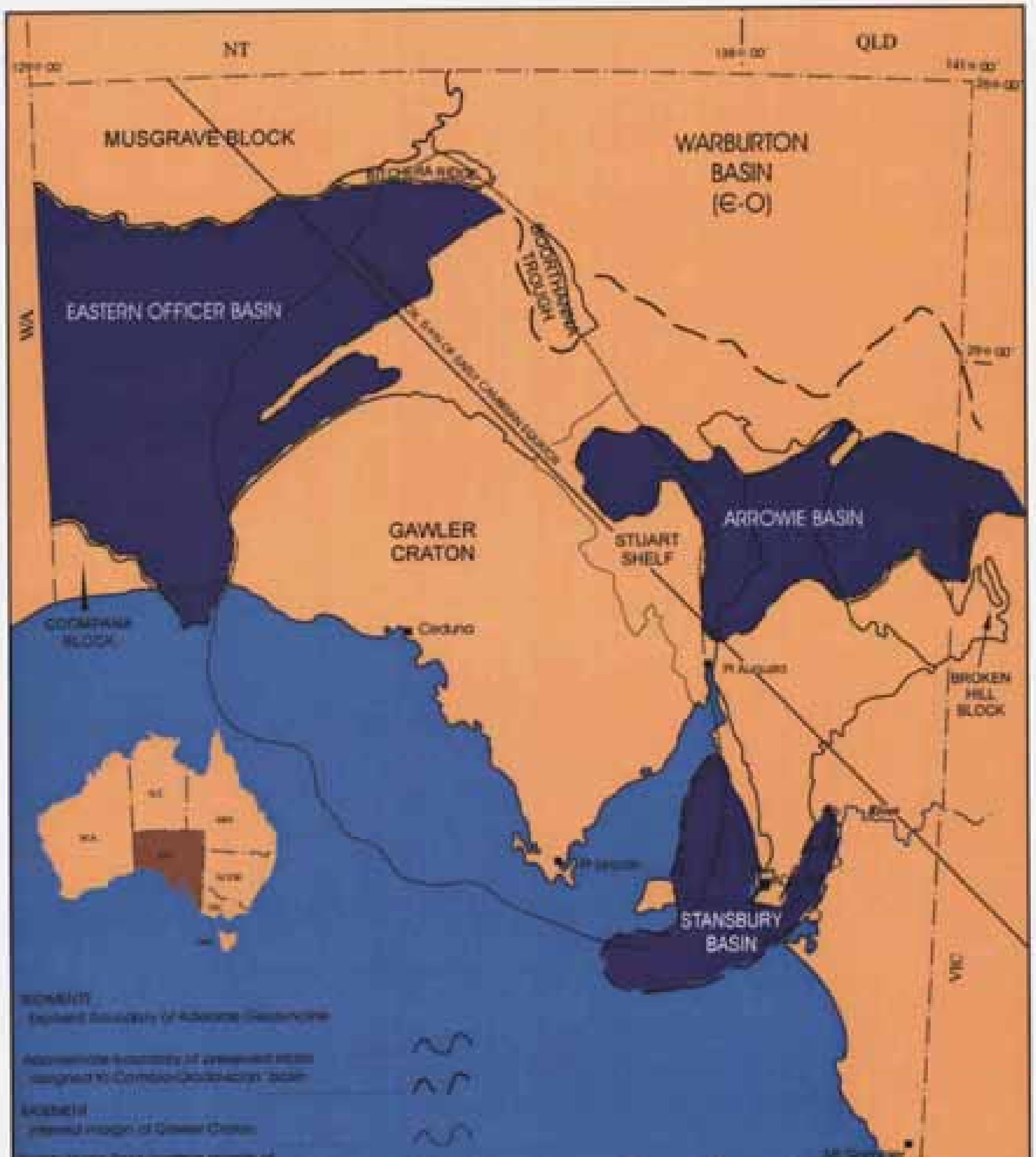


Figure 1. Cambro-Ordovician Basins in South Australia

CHINESE ANALOGUES RELEVANT TO S.A. BASINS

Tarim Basin

Regional and petroleum geology

The Tarim Basin (Fig. 2) is the largest and least explored inland basin in China. The basin coverts 560,000 km^2, approximately equivalent in size to the state of Texas in the United States The basin is fringed by high mountains of Palaeozoic fold belts of the Tianshan Mountains in the north, the Kunlun Mountains in the south, and the Aerjin Mountains in the southeast. The interior of the basin is mostly covered by the Takla Makan Desert, which extends for 330,000 km^2. The Tarim Basin experienced at least seven evolutionary events: 1) Sinian-Cambrian-Ordovician aulacogen stage; 2) Silurian-Devonian intracratonic depression stage, 3) Carboniferous marginal sea sage, 4) Permian rift basin stage, 5) Triassic-Jurassic foreland basin stage, 6) Cretaceous – Paleogene Neo-Tethys bay stage, 7) Neogene-Pleistocene foreland and inland basin stage (Fig. 3). The basin's Palaeozoic marine platform sequences and the Mesozoic-Cenozoic terrestrial fills are believed to contain substantial volumes of hydrocarbons (Li et al., 1996). The Tianshan fold zone is the principal source of sediment for the Tarim Basin.

Nine oil and gas fields have been found and 23 discoveries have been reported so far (Li et al., 1996). It has been proven by practice that the Tarim Basin is very rich in oil and gas resources. Output of crude oil was 52,000 BOPD in 1995. It is one of the three basins in China which have been predicted to have oil and gas resources over 10 billion tons (Gu et al., 1994).

The geological conditions in the Tarim Basin are complicated. The 15,000m thick sequence ranges from Neoproterozoic to Cenozoic, and includes marine and non-marine sedimentary rocks. The basin can be divided into several sub-basins not unlike the superposition of the Warburton, Cooper and Eromanga Basins, where each sub-basin was formed under a different tectonic regime. Its Sinian, Cambrian to Ordovician sequences can be correlated with those in South Australian basins, particularly the eastern Officer Basin.

The Sinian (=Marinoan) deposits contain a suite of continental glacial tillites and carbonate-siliciclastic sequence (Fig. 4). The late Sinian sedimentary rocks were deposited during a major marine transgression and can be divided into lower marls intercalated with thin-bedded shale, middle intraclastic limestone and upper dolomites, sandstones and shale. The entire Sinian sedimentary rocks can be up to 6000 m thick. Cambro-Ordovician deposits reflected

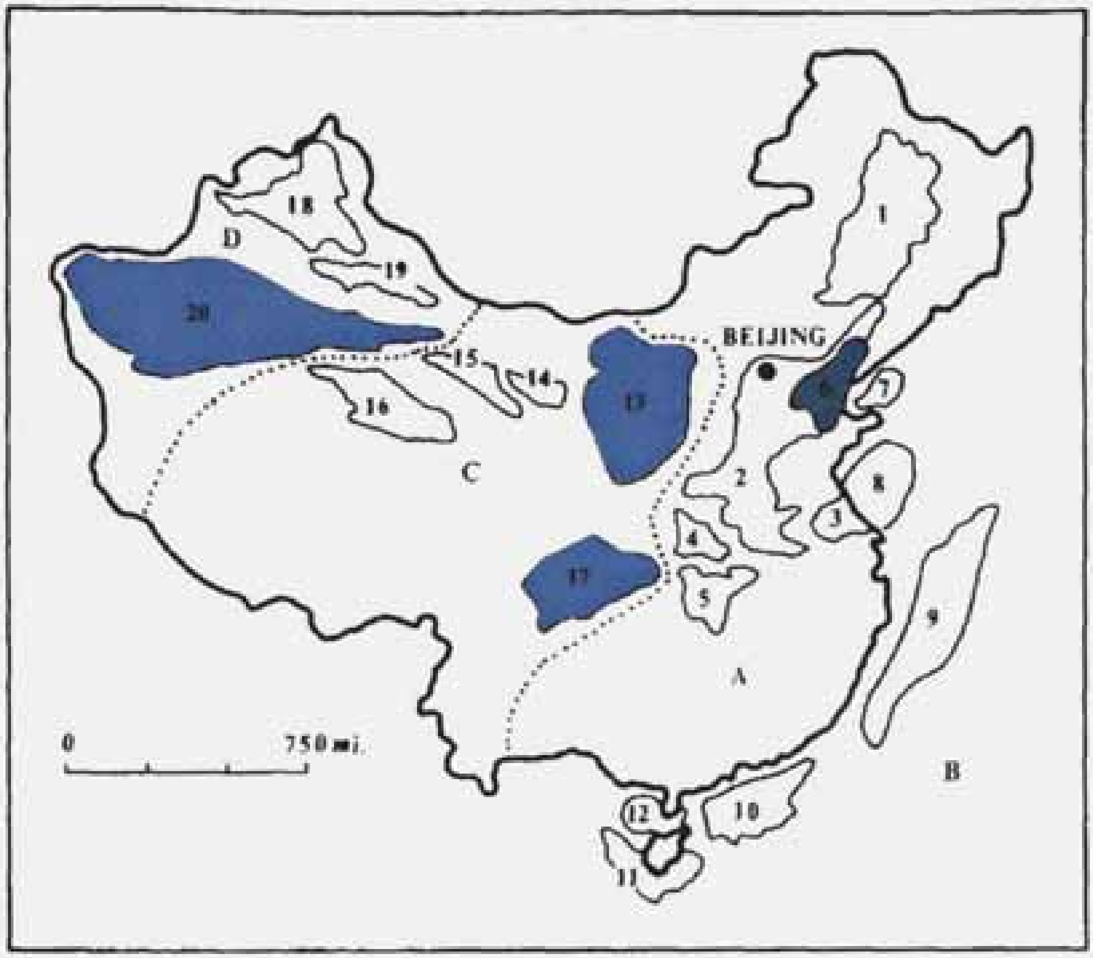


Figure 2. Major oil-bearing sedimentary basins of China (after Energy information administration, US department of Energy).

A. Eastern region basins (onshore):
1. Songliao; 2. Bohai (Huabei — southern onshore section of Bohai Basin); 3. Subei; 4. Nanxiang; 5. Jianghan.

B. Eastern region basins (offshore):
6. Bohai (offshore section); 7. North Yellow Sea; 8. South Yellow Sea; 9. East China Sea; 10. Pearl River Mouth (Zhujiang); 11. South China Sea (Yingge Sea, Yinggehai); 12. Beibu Gulf.

C. Central region basins:
13. Ordos (Erduos; Shanganning); 14. Zhaoshi (Ruoshi); 15. Jiuquan; 16. Chaidam (Qaidam, Tsaidam); 17. Sichuan.

D. Western region basins:
18. Junggar (Zhungeer); 19. Turpan (Turfan, Tulufan); 20 Tarim (Talimu).

the maximum marine transgression in the region. The Early Cambrian sequence consists of carbonaceous shale with siliceous phosphorites, dolomites, and thin-bedded limestone of a semirestricted platform environment. The maximum thickness of the Cambrian-Ordovician systems is over 3000m. At the end of the Ordovician, the entire Tarim Basin was elevated and underwent erosion during the late Caledonian Orogeny (Figs. 3, 4). Main petroleum production in the basin is related to Ordovician source and reservoirs.

Structural style

Being E-W trending, of multi-phases and complex-superimposed, the Tarim Basin is divided into several tectonic units: three uplifts and four depressions (Fig. 5). Each tectonic unit has different depocentres and different source, reservoir and seal combinations. The structural and stratigraphic characteristics vary among different units, as do the hydrocarbon prospects in different parts of the basin. Six major stratigraphic breaks are recognised from the Sinian to the Cenozoic. Thus, the origin, migration, accumulation, and redistribution of hydrocarbons in the basin are quite complicated. The youngest stage (Himalayan) Orogeny is the most prominent event in forming the overall basin shape, as well as oil and gas traps (Fig. 4). At the eastern part of the Central uplift, the Jurassic unconformity overlies an eroded Ordovician formation. In the Tazhong uplift, Carboniferous rocks unconformably overlie an Ordovician anticline, where the TZ 1 well (Fig. 6) tested Early Ordovician dolomites (3565-3737m depth) with a high flow rate of light crude oil at 3600 BOPD and natural gas at 360,000 m^3/d (12.7 MMCFD). The northern depression (Fig. 5) is considered the most prospective area of the basin, as it contains all the factors required of a petroleum system: source, reservoir, seal and trap.

Reservoirs and traps

The deepest (5953m) Ordovician carbonate reservoirs in China have been found in the basin (Gu et al., 1994). More than 41 Ordovician structural highs and 66 Carboniferous structural closures have been mapped by seismic survey. The principal types of traps discovered to date in the Tarim Basin are faulted anticlines (Li et al., 1996) (Fig. 7). The buried-hill traps are present at the Yakla and the Tazhong Gas and Oil Fields. The unconformity between the Triassic reservoir and the underlying Ordovician buried-hill trap plays an important role as both reservoir and pathway (Li et al., 1996). Lying on the Yakla structure (Tabei uplift), Cambro-Ordovician carbonate reservoirs dip 15-20° to the south in a monoclinal faulted block. The initial production from Shacan 2 yielded some 1000 m^3 of oil and 2 Mm^3/d of

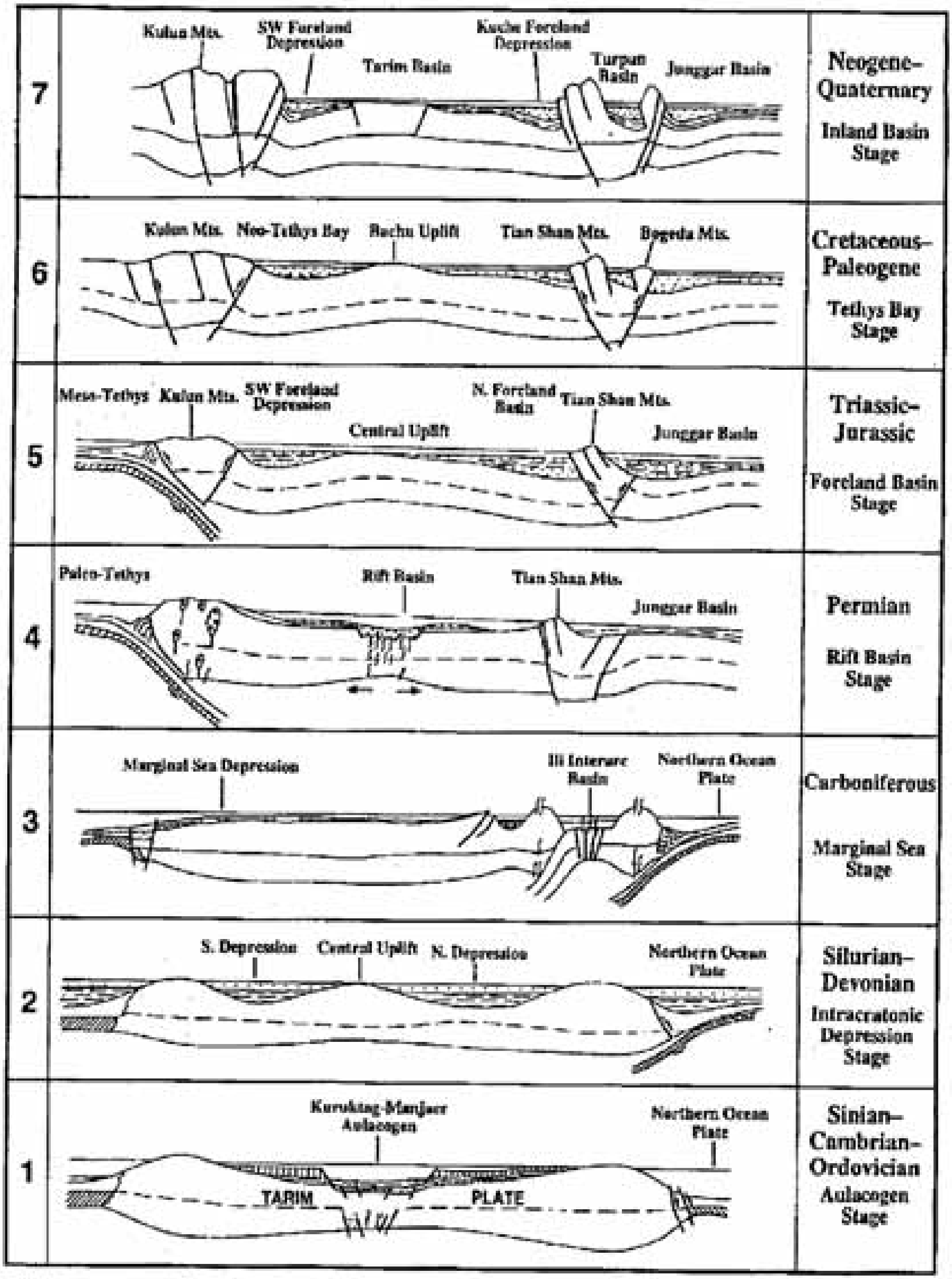


Figure 3. Tectonic evolution of the Tarim Basin (after Li et la., 1996).

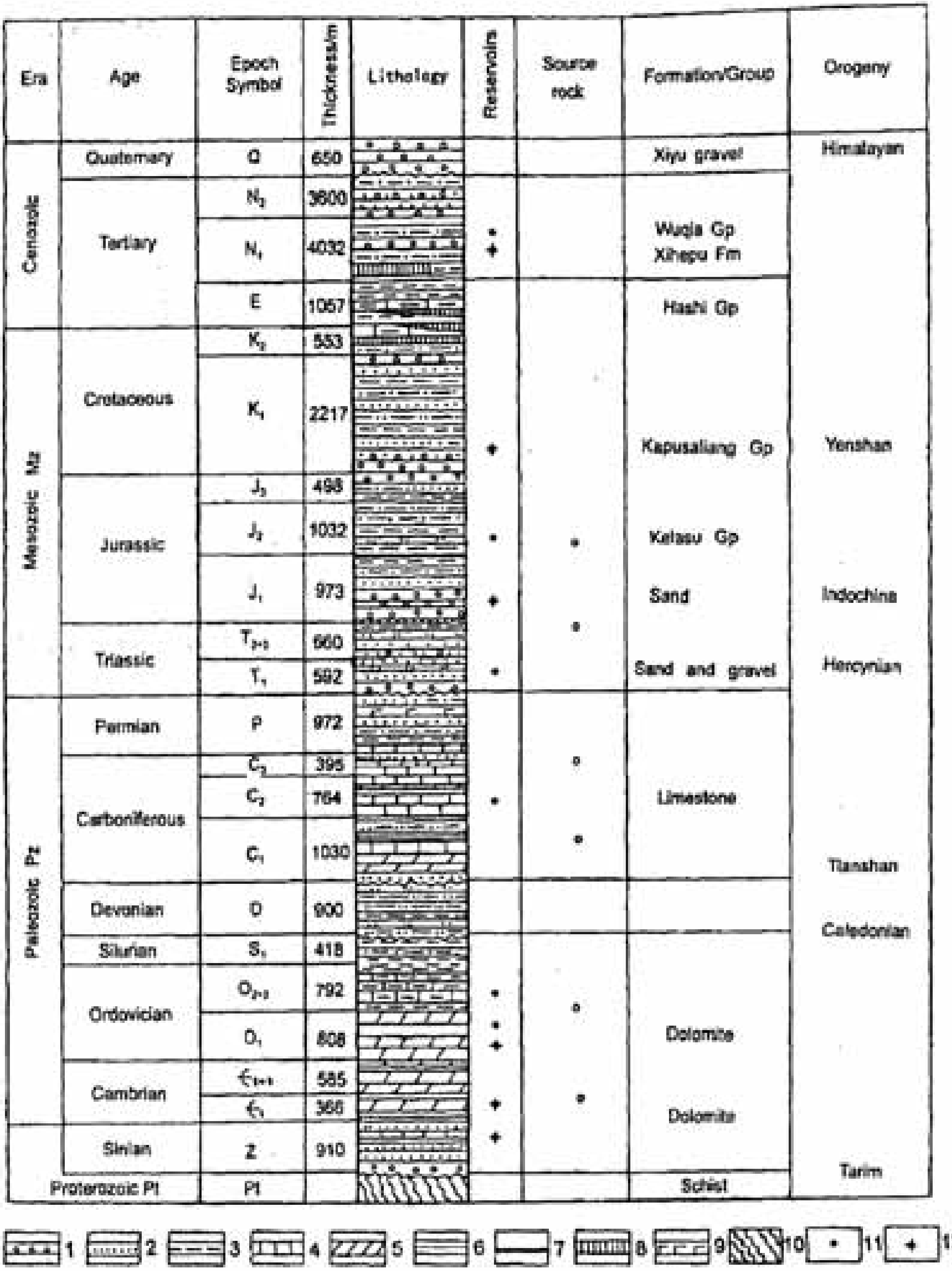


Figure 4. Composite stratigraphic section showingf major lithological characters and potential source rockunits in the Tarim Basin. Number denotes: 1=gravel, 2=sandsteon, 3=mudstone, 4=limestone, 5=dolomite, 6=shale, 7=coal, 8=anhydrite, 9=basalt, 10=schist, 11=oil reservoir, 12=oil and gas reservoir (Chen et al., 2000).

natural gas from the interval 5363m to 5392 m. Lunnan 1 tested Ordovician dolomite (5039-5300m), and yielded 97 m^3/d of oil after acid treatment. Lunnan 8 tested Ordovician dolomite from 5179-5266 m and obtained an oil flow of 564 m^3/d and 189, 000 m^3/d of natural gas.

Source rocks

All known gas in the Tarim Basin is thermogenic. One of the source rocks for the gas is the Sinian-lower Palaeozoic marine source rock, and the other is from terrestrial Triassic-Jurassic sedimentary rocks (Chen et al., 2000). The Sinian-lower Palaeozoic unit is up to 9500m thick and, except in the South uplift and the Southeast depression, is widespread. These strata, except for the Silurian and part of the middle-upper Ordovician deposits, are mainly marine carbonate sedimentary rocks. The Sinian-lower Palaeozoic units have had much tectonic activity and are highly mature in most areas, especially in the depression centers (Fig. 3). Many authors believe that the main source rocks in the Tarim Basin occur within the Cambrian-Ordovician marine sediment (Zhang et al., 1999).

The Cambrian-Ordovician marine source rocks include Early-Middle Cambrian and Middle-Late Ordovician muddy limestone and marl, which implies a value of over 2.0% vitrinite reflectance (Ro) equivalent and thus can produce only gas. The Middle-Late Ordovician source rocks, with vitrinite reflectance 0.81-1.3% (Ro), are an important source due to their lower (medium) maturity, wider distribution and thickness (Zhang et al., 1999; Liang, 1999).

Zhang et al., 1999 suggested that the best source rock in the Tarim Basin is the Liang-li-ta-ge Formation in the Tazhong depression. The TOC here ranges from 0.5% to 5.54%. The average thickness of the organic rich beds is ~80m with a known maximum of 300m in TZ 43. Vitrinite reflectance equivalence ranged from 0.81 to 1.3% in that well is mainly from the Liang-li-ta-ge Formation that is an organic-rich muddy limestone or marl, deposited in a platform edge to slope mud mound environment. The other good source rock, the Yin-gan Formation, was deposited in a semi-enclosed bay environment. It has TOC values of 0.5-2.1% and a thickness up to 97m (Zhang et al., 1999).

According to Liang (1999), the Cambrian source rocks include muddy limestone, muddy dolomite and siliceous mudstone, deposited under-compensated basinal and evaporative lagoonal environments. These rocks have TOC values of 0.5-5.2% (the highest up to 15.5%), Ro at 1.63-2.55%, and a thickness from 108m to 415m. The Cambrian sedimentary rocks show high to very high maturity, may be good for gas. The gas of the Hetianhe gas field in the

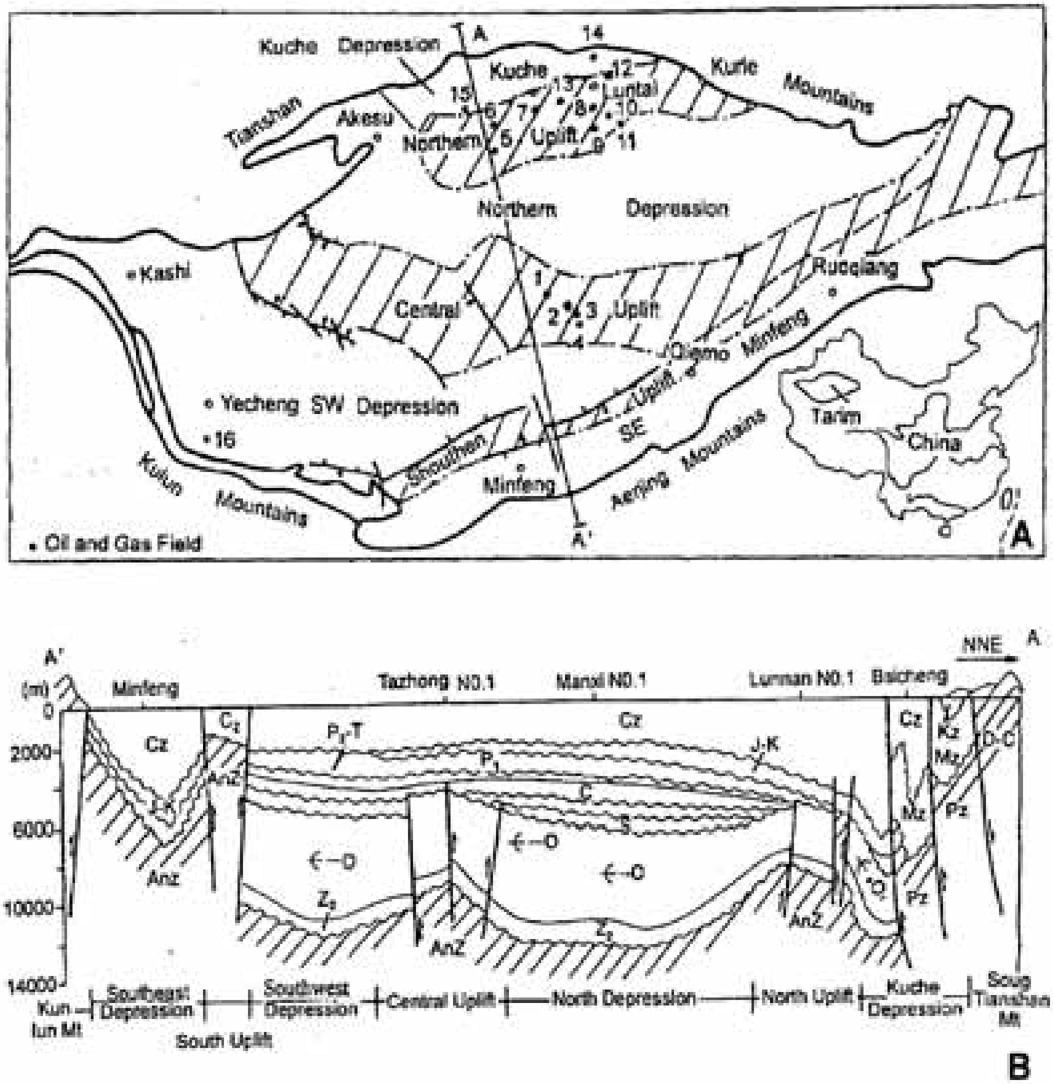


Figure 5. Major tectonic elements of the Tarim Basin (A.) and cross-section (B.) (After Chen et a., 2000).

central Tarim Basin was probably derived mainly from the underlying Cambrian deposits (Dai et al., 1999, 2000; Xia et al., 2000).

Maturity of the source rocks

Thermal basin-modeling by Zhang et al. (1999, fig. 6) indicated that the Early-Middle Cambrian source rocks formed early, evolved promptly and went through the oil window to the gas stage following the Late Caledonian Orogeny; whereas the Middle-Late Ordovician matured slowly, reaching the peak oil-generation window from Late Jurassic to present day (Yanshan to Xishan Orogenies). In this model, the large-scaled marine (Early-Middle Cambrian) source rocks in the Tarim Basin possibly entered the oil window around 500 Ma. They were likely to have been destroyed by several subsequent tectonic thermal events. The oil therefore, was probably sourced from the Middle-Late Ordovician rocks whose peak oil-producing periods occurred from Late Jurassic onwards. In other words, the large amount of crude oil was formed and accumulated post 200Ma of their deposition. This assumption is currently supported by structural analysis of oil accumulation, fluid inclusions and of authigenic mineral isotopes.

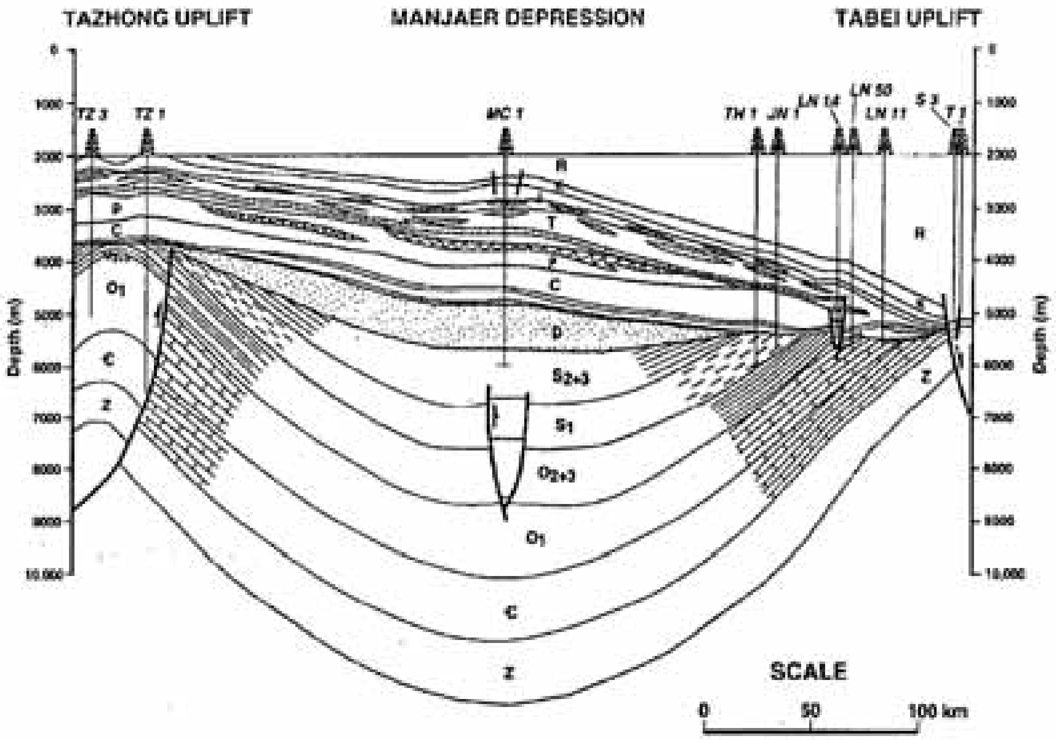
Both the basin's Palaeozoic marine platform sequences and Mesozoic-Cenozoic terrestrial fills contain substantial volumes of hydrocarbons. The Tarim Petroleum Exploration and Development Bureau estimated the in-place potential resources in the Tarim Basin in 1993 at 10.7 billion tons of oil and 8.4 trillion m^3 of natural gas. However, Hanson et al. (2000) ruled out the possibility of huge hydrocarbon reserves and suggested that exploration plays should focus on Ordovician and Triassic-Jurassic source rocks in several places in the basin.

Bohai Gulf Basin

According to Li (1990), the Bohai Gulf Basin, 200,000 square kilometres in area, hosted abundant oil and gas accumulations. The extremely complex geological structure (e.g. normal faults and numerous fault-block oil and gas traps) has made hydrocarbon exploration difficult. The application of traditional theory resulted in the location only of water instead of oil, while what were thought to be barren horizons have turned out to be petroliferous. In addition, oil-bearing horizons may be of varying thickness and depths. Chinese petroleum geologists have proposed and developed the theory of composite megastructural oil and gas accumulations, showing that different pay-horizons and trap-types may evolve in similar ways and interact with each other: joint, superimposed 'traps' may then form a megastructural oil-gas 'belt'. As a result of these methods, eight 'giant' accumulations and 144 oil-traps, (of which 100 are producing), were discovered. Since 1986, crude oil production in the Bohai Gulf Basin has reached 60MM tons/year (1.2MMBOD). More oil and gas fields have been found since 1990, especially in Ordovician buried hill-type reservoirs but sourced from Tertiary continental deposits (Dr Ma Li-qiao, CNPC, pers. comm. 1999). Six conceptual models for megastructural oil and gas "belts" are summarized below from Li (1990, fig. 4):

1. Central anticline, composite megastructural belt.

2. Low, buried-hill, composite megastructural belt.
3. Highly uplifted, composite megastructural belt.
4. Synsedimentary fault and rollover anticline, megastructural, composite belt.
5. Structural slope, composite megastructural belt.
6. Basin trough, lithological composite megastructural belt.



Ordos Basin

The Ordos Basin is located in central-north China and has been an important petroleum province since the world-class Changqing Gas Field was found in the early 1990s. Gas reserves are mainly in Palaeozoic carbonate reservoirs (weathered crust) (Fig. 8c). Weathered clay crust formed a seal over the reservoirs. This unconformity surface represents a 150 Ma hiatus, which functioned as both reservoir and petroleum migration pathway.

Reservoirs

The reservoirs of the Changqing Gas Field comprise mainly karstic and vuggy carbonate (Fig. 9) related to the weathered carbonate rocks and formed as an anticline structure on the Shanbei Slope. The reservoirs are unique as they have: no-structural control, no-single source and the gas is stored in rocks with lower permeability (Ma et al., 1999). Reservoir rocks are mainly Ordovician carbonates, but sources are considered to be from Carboniferous-Permian coal beds and Ordovician organic rich silty carbonates (discussed below). Late Palaeozoic uplifting by Caledonian events probably gave rise to weathering and the development of karstic reservoirs.

Source Rocks

The Changqing gas field in the Ordos Basin produces gas from karsted dolostone of the Early Ordovician Majiagou Formation beneath the Carboniferous/Ordovician unconformity. Overlying the Ordovician are coal measures with limestone (20-30m) interbeds in the Carboniferous Taiyuan and Benxi Formations. Evidence indicates that the Carboniferous-Permian coal measures are the main source rock of the gas produced from the Majiagou Formation (Dai et al., 1999, 2000). The average of TOC value from over 600 samples of the Majiagou Formation is less than 0.2%. The Carboniferous-Permian coal measures, however, have TOC values of 1.37-2.07% for dark mudstone and 62.9-72.5%. Natural gas from the Majiagou Formation has $\delta^{13}C$ values that are similar to those of the Carboniferous-Permian coal measures. Carbonate isotopic distribution of individual hydrocarbons in the condensates from the Ordovician gas pools is also similar to that of the Carboniferous-Permian condensates.

Traps

The seal for the gas fields comprises siltstone or silty carbonates overlying the karstic carbonates. The fine-grained siliciclastic rocks probably were deposited in trough or depression settings and became natural barriers preventing gas migration up-dip (Ma et al., 1999).

Relevance to South Australian basins

Eastern Warburton Basin

Four wells (gas in Lycosa 1 and Moolalla 1, and oil in Sturt 6 and 7) in South Australia have tested commercial flows of hydrocarbons. Reservoirs from Lycosa 1 (siltstone), Sturt 6, 7 (ignimbrite), Moolalla 1 (fine-grained sandstone) and recently Challum 19 (carbonate rock) in Queensland are all Cambro-Ordovician in age. More than 90 wells have petroleum shows (Sun & Gravestock in prep.). Similar to the Tarim, Bohai Gulf and Ordos Basins, the Warburton Basin strata are faulted and fractured, and unconformably underlie or are tectonically/unconformably juxtaposed with the productive Cooper and Eromanga Basins. The geochemistry data indicated that hydrocarbons probably migrated from Cooper Basin source rocks into older Warburton Basin reservoirs. Similarly, the buried hill-type Cambro-Ordovician carbonate reservoirs in the Chinese basins contain hydrocarbon from overlying younger source rocks such as from Carboniferous-Permian coal measures of the Ordos Basin.

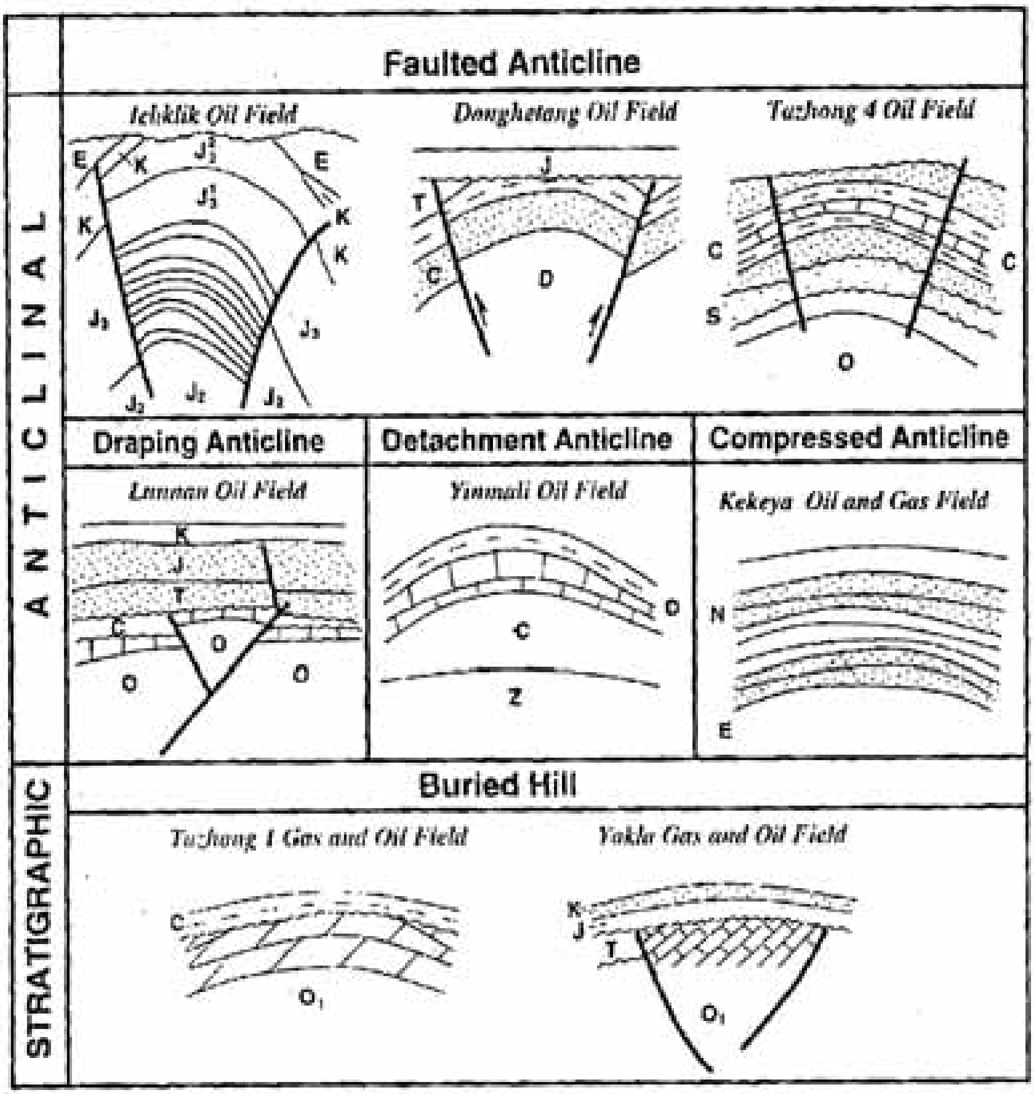


Figure 7. Oil and gas trap types of the Tarim Basin. Stratigraphic fields show post-unconformity structuring (Li et al., 1996).

Although the source is considered to have been from the overlying Cooper Basin, there may be some chance for a Cambro-Ordovician source presence. Organic rich muddy limestone is very common in the deeper water carbonate mudstone of the Kalladeina Formation; also some lagoonal deposits in the Coongie area may be organic rich. The limited data of TOC values from the formation can reach as high as 0.89% (Roberts et al., 1990; Sun, 1996, 1998). The study suggests that Warburton Basin potential source rocks are mature, varying from the oil window to gas. It is possible that a source-reservoir combination is also present in the Warburton Basin. The overlying Cooper Basin source makes the uppermost 200m or so of Warburton rocks highly prospective for petroleum exploration. The prominent unconformity between the Warburton and Cooper Basins is regarded as a reliable petroleum migration pathway. Weathered Warburton Basin rocks, especially the shale and siltstone of the Dullingari Group, may provide seal (Gravestock et al., 1999).

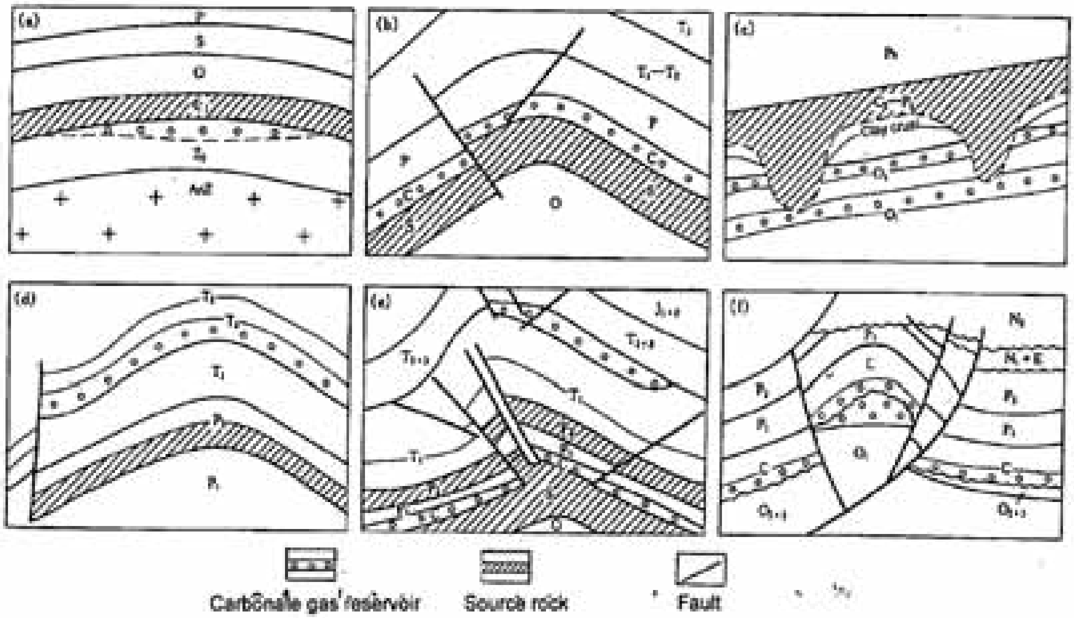


Figure 8.Cross sections of giant carbonate gas reservoirs in China. a=Weiyuan Gas Field, b=Wubaiti Gas Field, c=Changqing Gas Field, d=Moxi Gas Field, e=Wolonghe Gas Field and Hetian Gas Field.

Eastern Officer Basin

Oil bleeds (Byilkaoora 1, 1979) and oil shale (Wilkinson 1, Kamali et al., 1995) have been reported in Cambrian Ouldburra and Observatory Hill Formations. The potential Cambrian source rocks in the basin are overlain by porous potential reservoir rocks–Late Cambrian and Ordovician sandstones (Morton and Drexel, 1997). While the siltstone of the Devonian Mimili Formation would form an effective seal. This combination of source-reservoir-seal may be present in the Munyarai, Manya and Tallaringa Troughs.

Neoproterozoic and Cambrian source rocks and seals in China, Siberian and Oman

Weiyuan Gasfield, Sichuan Basin

The Weiyuan gasfield in Sichuan, central China occurs in the oldest carbonate reservoir (Upper Sinian Dengying Formation, latest Neoproterozoic). Sinian carbonates were previously considered to be both source and reservoir for the largest and oldest natural gas accumulation. The reservoir rocks are Sinian algal dolomite of about 650m thick, and the porosity is vuggy and interconnected by fracture systems. The seal is dark grey shale of the Lower Cambrian Qiongzhusi Formation (~230m thick, Xu et al., 1992). The source rocks are either Dengying Formation (TOC=0.12%, n=1143) or Qiongzhusi Formation (TOC=0.97%, n=150); whereas biomarkers in the Dengying reservoir bitumen, especially 10-demethylhopane, methylhopane and steranes suggests that the source is more likely to be the Lower Cambrian shale (Dai et al., 1999, 2000). These carbonate source rocks have the highest burial temperature and over-maturity level for natural gas in China.

Siberian

Siberian Platform oils were probably sourced within the Vendian/Cambrian carbonate sequence. Carbon isotope signatures comprise a pattern also seen in other organic matter of Vendian age, including the Huqf Group oils of Oman. They are apparently associated with special features of the biology and palaeoenvironment that existed during the latest Proterozoic. The oils are indigenous to a complex sedimentary sequence of Late Proterozoic and Cambrian rocks. They could be derived from deeply buried, basinal organic-rich shale of Riphean age or from a Vendian to Cambrian shelf carbonate and clastic sequence in which they are reservoired (Summons & Powell, 1992 and reference therein). The TOC values range 0.5-8% (Liang et al., 1999).

Oman

Oil in Oman was probably sourced from Cambrian sedimentary rocks (Simmons, 2000). It is well known that Oman oil is related to evaporitic sediments and salt structures. Cambrian evaporite and salt deposits in the eastern Officer Basin (Ouldburra and Observatory Hill Formations) may have similar geological conditions and petroleum prospectivity.

Relevance to South Australian basins

Neoproterozoic rocks in Australia so far not known to contain commercial volume of petroleum flows though some shows have been discovered in the Bitter Springs Formation in the Dingo Field of the Amadeus Basin (Roe, 1991). Oil shale is present in the McArthur

Basin, but effective reservoir rocks have not yet been found. In South Australia, such comparable sequences can be found in the eastern Officer Basin and possibly the Arrowie Basin, where porous carbonate and sandstone reservoirs are widely distributed and fair Cambrian source rocks were reported (McKirdy, 1994; Morton and Drexel, 1997; Harvey and Hibburt, 1999). McKirdy (in Gravestock *et al.*, 1987) has compared general geochemical characteristics of Cambrian potential source rocks in South Australia, including the Warburton, Arrowie and Officer Basins.

COMPARISON BETWEEN THE CHINESE AND S.A. BASINS

Source rocks in South Australian basins

A study of the petroleum potential in Cambrian sedimentary basins in South Australia commenced after waxy paraffinic crude was found in Wilkatana 1 in the Arrowie Basin in 1956. Some fifty exploration wells were drilled between the 1950s and 1970s, but most of were not on structures because of poor understanding of the tectonic evolution and sedimentation. Subsequent studies suggested a complex oil generation and migration history in Cambrian sedimentary rocks and the existence of potential source rocks (McKirdy, 1994). Generally, a lack of sufficient source rocks makes exploration in the Cambro-Ordovician frontier basin in South Australia high risk.

The stratigraphy of the Warburton Basin is similar to that in the Ordos Basin. The time gap of the unconformity between the Ordovician marine carbonate reservoirs and the overlying Carboniferous or Permian continental deposits in the two basins are similar-about 150 Ma. They similarly yield unconformity-related, Cambro-Ordovician, karsted carbonate reservoirs with hydrocarbons originated from the overlying younger continental deposits.

Reservoir characteristics of Chinese producing carbonate reservoir rocks

Cambrian carbonates are normally deeply buried in South Australia, especially in the Warburton, Stansbury and Arrowie Basins. Most drillholes are not deep enough to test the carbonate reservoirs predicted. Frijole 1 in the Stansbury Basin, for example, bottomed in the red-brown siltstone of the Yuruga Formation (interpreted as seal rocks), whereas desirable carbonate sequences were not penetrated. Considering that most petroleum fields in the Tarim Basin occur 5900m below the surface, deep-buried carbonates are yet to be explored in South Australia.

There are many productive carbonate reservoir rocks in the above-mentioned Chinese basins. Table 1 summarises the characteristics of some carbonate reservoir rocks from several well-known oil and gas fields.

Potential reservoir rocks in S.A. basins

Characteristics of some potential reservoir rocks are well studied in the Officer Basin (Harvey and Hibburt, 1999, p.90; Kamali et al., 1995), Arrowie Basin (Harvey and Hibburt, 1999, p.78) and Stansbury Basin (Harvey and Hibburt, 1999, p.83). Besides the fractured reservoirs (Sun, 1999; Sun & Gravestock, 2001), there are several kinds of reservoirs recognised in the Warburton Basin (Roberts et al., 1990, Sun, 1996, 1997b, 1998; Sun & Gravestock, in prep.).

Peritidal carbonate

The Diamond Bog Dolomite and Coongie Limestone Member represent two separate peritidal carbonate successions. Up to 27.5 mD permeability has been measured in oomoldic dolomite from Coongie 1 (Fig. 10).

Karsted carbonate

The Diamond Bog Dolomite contains vuggy and intercrystalline porosity. Karstification, due to subaerial exposure, occurred at the sequence boundary between depositional sequence 1 and 2 (Sun, 1998). This type of reservoir is predicted to occur parallel to and deeper than the inferred NE trending shelf-edge for depositional sequence 3 (Sun, 1996, 1997b, 1998). Most Warburton Basin strata intersected immediately below the Cooper/Eromanga Basins are siliciclastic rocks except in Gidgealpa 7, 16, 19, 23 and 36 and Cuttapirrie 1. Only Gidgealpa 23 and 36 contained shallow-water grainstone, while the others are either micritic limestone or deep-water lime mudstone. A cuttings thin section in Gidgealpa 23 immediately beneath the unconformity shows good secondary porosity. A cuttings thin section from the interval 2255.52-2258.57 m in Gidgealpa 19 also displays excellent vuggy and intercrystalline porosity in dolomite. Thus, potential karsted carbonate reservoir rocks should exist wherever karst-prone, shoal-water carbonate or sandy limestone occur immediately underlie the unconformity between the Warburton Basin and overlying younger basins and also at the three depositional sequence boundaries within the Warburton Basin (Sun, 1998).

Table 1 Characteristics of some Chinese petroleum-producing carbonate reservoir rocks (selected from Table 1 of Xia et al., 2000)

Gas field (basin)	Main producing reservoir bed / (main source rock)	Lithology	Thickness (m)	Porosity %	Permeability ($x10^{-3}$ μm^2)
Changqing (Ordos)	Ordovician (Carboniferous-Permian coal measures)	Dolomite	10-15	Ave. 4.05-8.20	Ave. 0.85-18.7
Weiyuan (Sichuan)	Sinian (NPt) (Early Cambrian Qiongzhusi Fm.)	Algal dolomite	10-25	Ave. 3.22	Ave 1.00-38.6
Hetianhe (Tarim)	Lower Carboniferous	Bioclastic limestone	30-36	Ave. 3.55	Ave. 2.23
	Ordovician (E.-M. Cambrian source)	Bioclastic, oolitic, sandy limestone	165-354 (buried hill)	Ave. 6.85	Ave. 2.38
Wubaiti	Upper Carboniferou	Dolomite	19-28	0.06-21.31	0.01-9.78

Ignimbrite reservoir rock

Porosity has developed in coarse-grained ignimbrite of the Taloola Ignimbrite as a result of feldspar dissolution (e.g. in Taloola 1 and Sturt 7 and 8). This facies produces oil in Sturt 6. Besides matrix porosity due to dissolution, brittle fracture permeability has developed.

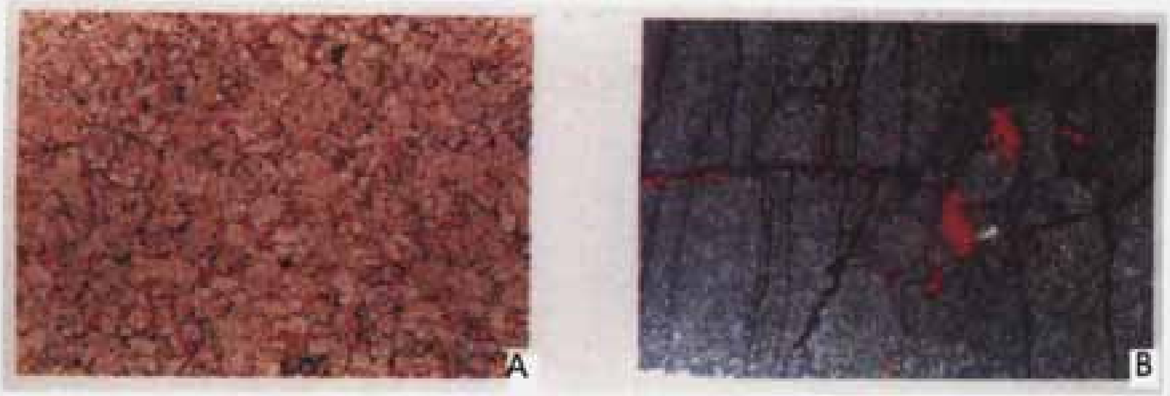


Figure 9. A. Photomicrograph, coarse intercrystalline and vuggy dolomite from unit 5, the Ordovician Majagou Limestone, Yu-3 (well), Ordos Basin, China. x40.
B. Photomicrograph, intercrystalline and vuggy dolomite showing fractures and breccia interconnecting isolated pores, from unit 5, depth: 3325.5m, the Ordovician Majagou Limestone, Shan-42 (well), Ordos Basin, China. x25.

Sandstone reservoir rock

There are two main types of sandstone. One was deposited in shallow marine shoreface to shelf environments, and the other in a deep marine basinal environment. Sandstones are classified according to visual estimates of percentage of quartz, feldspar and rock fragments in thin sections. The shoreface and shelf facies sandstone is dominated by clean quartzarenite such as the Pando Sandstone, subarkose and sublitharenite, with minor arkose (e.g. Kalladeina 1, core 4), whereas the basinal sandstone facies is poorly sorted, angular greywacke (Sun & Gravestock, in preparation).

Furthermore, in other South Australian Palaeozoic basins, reservoir rocks are also relatively well developed, including both carbonate and sandstone rocks. The potential reservoir rocks include dolomite, limestone karst and sandstone. For example, the Wirrealpa Limestone has porosity up to 11% and permeability up to 1.8mD measured from core in Moorowie 1 in the Arrowie Basin (Harvey & Hibburt, 1999). In addition, the Early Cambrian Archaeocyatha reef and shelf-edge buildup have been studied by James & Gravestock, (1990). Potential dolomite and sandstone reservoirs were described from the Officer Basin (Kamali et al., 1995). These studies provide better understanding of their petroleum prospectivity in the South Australian basins (see Harvey & Hibburt, 1999 for detail).

For example, recently Zang and Tucker (2000) illustrated different reservoir rocks in the Stansbury Basin, as well as source rocks and seals (Table 2).

Table 2. Petroleum data and summary in the Stansbury Basin (Zang and Tucker, 2000). TOC: total organic carbon content; Type II: oil prone; Type III: gas prone.

Reservoir Rocks		
Carbonate Reservoirs	Dolomitised limestone (Kulpara Formation)	Up to 500m thick, vuggy, dissolution and fractu core porosity up to 13%, permeability up to 340mD
	Koolywurtie reef complex	Up to 73m thick, vuggy and dissolution porosity
Sandstone Reservoirs	Winulta Formation (lower sandstone)	100m thick, arkosic, fluvial to shoreface sandsto lowstand deposits
	Stokes Bay Sandstone	~350m thick, shoreface sandstone, dissolution poros
	Yuruga Formation	>500m thick, lower part of sandstone, lowstand fluv arkosic with basal conglomerate
Seal		
Micritic Parara Limestone		Potential seal to the dolomitised limestone of Kulpara Fmn and sandstone of the Winulta Formatio
Minlaton Formation (siltstone + gypsum laye		Potential seal to underlying carbonate reservoirs
Yuruga Formation (upper siltstone)		Potential seal to all underlying reservoirs
Source Rocks		
Heatherdale Shale or equivalents		TOC (max. = 2.43%, mean = 0.64%), Kerogen type II
Parara Limestone		TOC (max. = 0.91%, mean =0.30%), Kerogen type II-III
Corrodgery Formation		Marine dark-grey shale (TOC = ? >0.5%), palaeo-temperat <110°C (estimated from acritarch's colour index).

In the above-mentioned Chinese basins, the reservoir rocks can include Sinian, Cambrian, Ordovician, Carboniferous, Triassic, Jurassic, and Tertiary, whereas the Ordovician, Carboniferous and Tertiary rocks are the main reservoir rocks. Most gases were generated from condensate-associated gas reservoir and oil-associated gas (Zhou, 1995). The Middle-Late Ordovician carbonate reservoirs in the Tazhong area of the Tarim Basin and vuggy dolomite in the Majiagou Limestone, Ordos Basin (Fig. 9) have excellent secondary porosity and permeability including vuggy and fractures. Similar secondary porosity also exists in South Australian Palaeozoic basins such as potential carbonate reservoir rocks in the Warburton Basin (Fig. 10) (Sun, 1996, 1997b, 1999; Sun & Gravestock, 2001), the Arrowie Basin (James & Gravestock, 1990), Stansbury Basin (Zang & Tucker, 2000), and the Officer Basin (Kamali et al., 1995).

Fig. 10. B. Photomicrograph, stained thin section,below, SEM photo; oomoldic dolomite from Coongie 1; E-F, vuggy dolomite, showing vuggy porosity: E. Photomicrograph, F. CL photo; D, core slab, showing vuggy and fractured dolomite from Gidgealpa 5 (from Sun, 1996, 1997b)

Traps in the Chinese basins

According to Dai et al. (1999, 2000), four types of traps are known from Chinese discoveries in Palaeozoic basins (Fig. 8). Anticlinal types formed small to big petroleum fields and most anticlinal structures in the Tarim Basin were formed during the Himalayan Orogeny. Palaeohigh structural types are commonly formed during the Himalayan Orogeny, which could contain over-mature or re-migrated gas to form large gas fields. Lithological types on the palaeohigh or in non-structural strata could form "cool" gas reservoirs to produce small to medium gas fields. Palaeokarst type formed traps (buried hill) often by lithological combination, for example, of karstic carbonate reservoir overlain by siltstone seal. The first two belong to structural traps such as those in the Tarim Basins (Figs. 8e, f), and the last two are related to stratigraphic traps such as those in the Ordos (Fig. 8c) and Sichuan Basins (Fig. 8a).

Structures and trap potential of S. A. basins

Structural traps are poorly known in South Australian Palaeozoic basins due to an absence of either useful seismic coverage in the Arrowie and Stansbury Basins or good quality seismic data in the eastern Officer and Warburton Basins. Some thrust fault related structural traps are recognised in the eastern Warburton Basin (Sun, 1997a) (Fig. 11) together with some stratigraphic traps (Sun, 1996, 1997b, 1998). Some sixty exploration wells were drilled in the Officer, Arrowie and Stansbury Basins since the 1950s, but most of them were not on structure because of poor understanding of the tectonic evolution and sedimentation. Many structures are now better known in the eastern Officer and Stansbury Basins after comprehensive study of TEISA assisted programs (Zang, 1995; Hoskins & Lemon, 1995; Flöttmann et al., 1998).

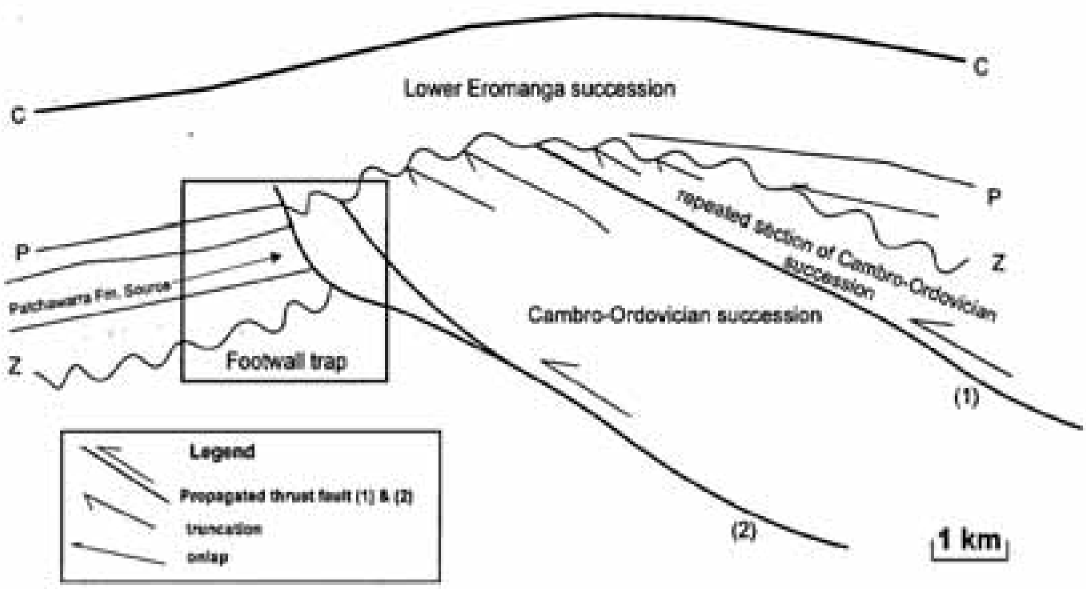


Figure 11. Schematic diagram based on seismic interpretation of seismic section 89-CHN, illustrating potential footwall trap (after Sun, 1997a).

As summarised by Harvey & Hibburt (1999), traps including simple domes and faulted anticlines to salt swells, pillows and salt walls were recognised from the eastern Officer Basin. Neoproterozoic thrust zones were reactivated in the Late Devonian and provide trap opportunities close to the Musgrave Block and on the northern margin of the Manya Trough. The largest fault complex strikes northeast-southwest almost 140km, with vertical displacements up to 2km; hanging wall anticlines are the principal targets for exploration. In the Stansbury Basin, structures with trap potential are fault-dependent and mainly concentrated in the north-northeast striking Pine Point Fault Zone adjacent to the east coast of Yorke Peninsula. Simple domes may underlie northern Gulf St Vincent and the north Adelaide Plains near Dublin, and may provide traps for gas.

CONCLUSIONS

Comparison of Chinese hydrocarbon producing Cambro-Ordovician sequences, particularly from the Tarim, Ordos, Bohai Gulf and Sichuan Basins with several South Australian basins of similar age indicates a similarity in terms of stratigraphy, sedimentology, structural style and reservoir quality. Stratigraphically, the Ordos Basin is similar to most of the South Australian Basins, especially the Warburton Basin in the following aspects: an hiatus with a time gap of about 150 Ma at the unconformity between the Ordovician marine deposits and overlying Carboniferous or Permian continental deposits, and a weathered crust forming a seal above or below the unconformities.

Fair to good quality Cambro-Ordovician carbonate reservoir rocks have been recognised in the Warburton, Officer, Stansbury and Arrowie Basins in South Australia. Hydrocarbons in commercial quantities have been discovered in the Warburton Basin together with numerous shows. Also some oil bleeds have been reported from several shallow drillholes in the Officer and Arrowie Basins. The secondary porosity of these carbonate reservoirs are similar to those in the Chinese producing oil and gas fields.

There are structural and stratigraphic traps recognised in the South Australian basins in particular the thrust and anticlinal structural traps in the Warburton and Officer Basins. Similar source rocks were reported in the South Australian Basins. These are all comparable to those of the Chinese basins. Thus, the South Australian basins may well have potential for further exploration, particularly at the unexplored deeper part of the basins.

One significant difference between the Tarim Basin and the South Australian Basins is that the Quaternary Himalayan Orogeny (a much more active and younger event) created important and younger structural traps. The orogenies in the South Australian Basins, such as the Alice Springs Orogeny (450-300Ma or Devonian-Carboniferous), which influenced the Warburton Basin the most, are much older events. The other difference is that marine deposits in the Tarim Basin lasted longer (as late as Permian) than those in the South Australian Basins (as late as Devonian in the Officer Basin).

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