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Sedimentology of Triassic Dounan-type manganese deposits, western margin, Yangtze Platform, China

Hongjun Liu *, Youzhi Xue

Southwest Geological Research Institute, Ministry of Metallurgical Industry, Erxianqiao, Chengdu, 610051, China

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Abstract

Manganese (Mn) deposits formed during the Ladinian (Middle Triassic) are widely distributed along the western margin of the Yangtze Platform. All the Mn deposits occur in condensed sections (CS) and are formed in similar depositional and structural settings related to late-stage incipient spreading of the Tethys seaway. Differences in the degree of development and sedimentary facies in different areas determined the size, ore-body strike and dip, and ore composition. Four sedimentary facies occur: (1) dolomite-rich Mn rocks, (2) glauconite-bearing oolitic Mn rocks, (3) phosphatic Fe-rich Mn rocks, and (4) silica-rich Mn rocks. Type 1 formed along the margin of a passive, stable margin; type 2 formed on basin slopes with relatively low topography and deep water; and types 3 and 4 formed mainly in the Ma'erkang Basin, a deep depression on the shelf. Ore constituents partly derived from a western source area formed medium- to low-grade ores in offshore areas during the Ladinian maximum sea-level rise. Ocean currents and lower-cycle sea-level changes produced composite ore beds. Seafloor hydrothermal systems typical of Tethyan rifting may have provided Mn-bearing fluids that ascended along faults and mixed with bottom currents. Those fluids and/or diagenetic oxidation reformed and concentrated the previously formed medium- to low-grade ore bodies. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Mn deposits; sedimentology; Yangtze Platform; Triassic; Tethyan tectonics

1. Introduction

The Dounan-type deposit is the general name for manganese (Mn) ores that formed during the Ladinian (Middle Triassic), in an area bounded to the north by Pinwu–Heishui in northwestern Sichuan Province and to the south by Jianshui–Wenshan in southeastern Yunnan Province (Fig. 1). Seven medium-size (>2 to <20 million metric tons) Mn deposits have been studied so far, including the Dounan, Baixian, and Heishui deposits (Fig. 2). There are also more than 80 small deposits or prospects. The total identified Mn ore reserve is about 50 million tons, which constitutes 8% of China's reserves. With the exception of a few individual deposits (e.g., Huya), these Mn ores are commonly of high quality and moderate grade. High-grade electric discharge (battery grade) Mn ores (e.g., Baixian) formed by supergene processes. The Dounan Mn deposit is one from the district that has been studied in detail (Zhang, 1985).

In order to determine the nature of the depositional basin during Ladinian metallogenesis, we drew Early Triassic and Middle–Late Triassic paleogeo-

* Corresponding author. E-mail: xnygkckf@mail.sc.scinto.net

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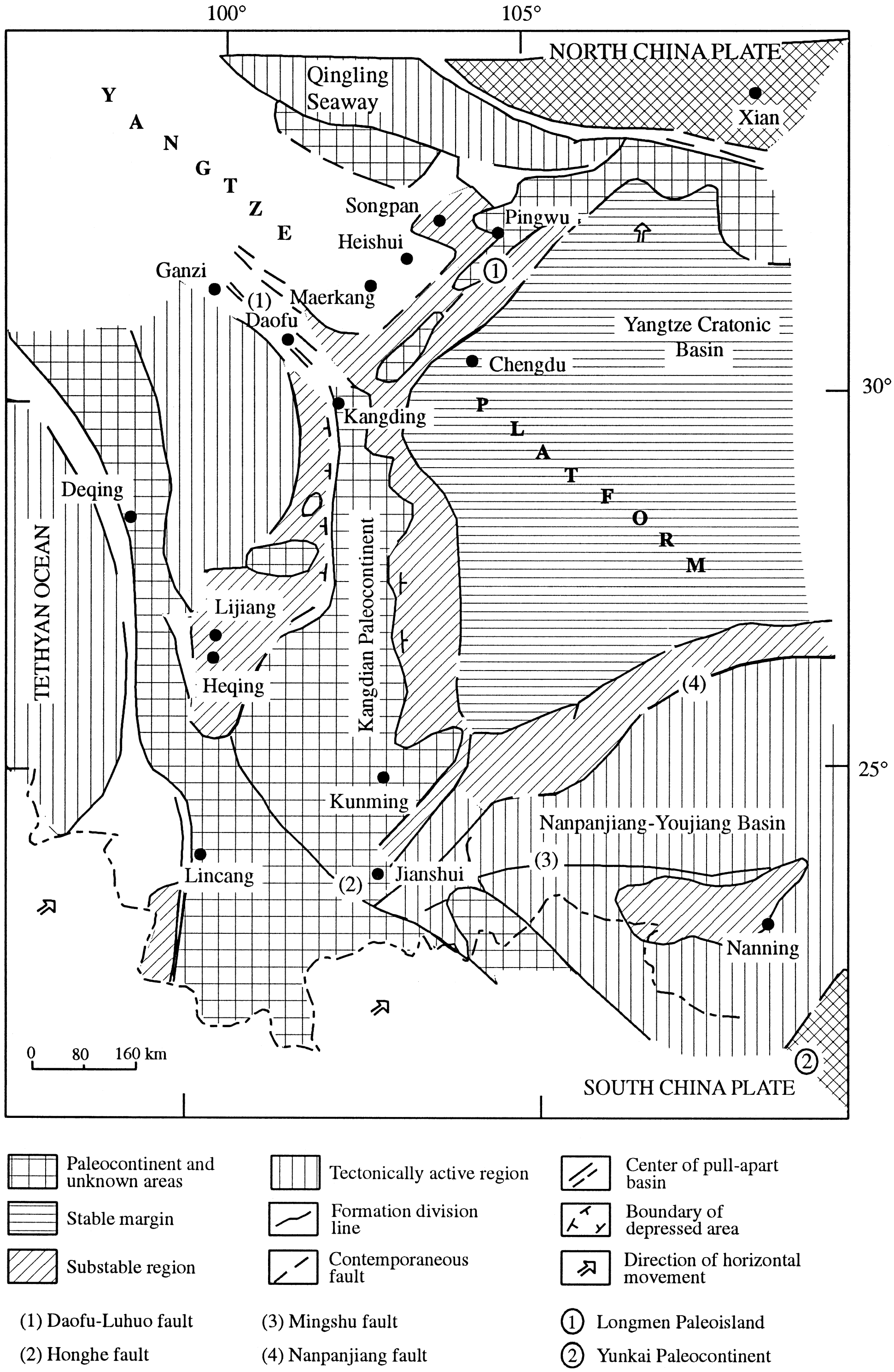

Fig. 1. Paleogeographic map for the Early Triassic showing the Paleo-Tethyan tectonic region and the western margin of the Yangtze Platform; substable region means moderately tectonically and volcanically active region.

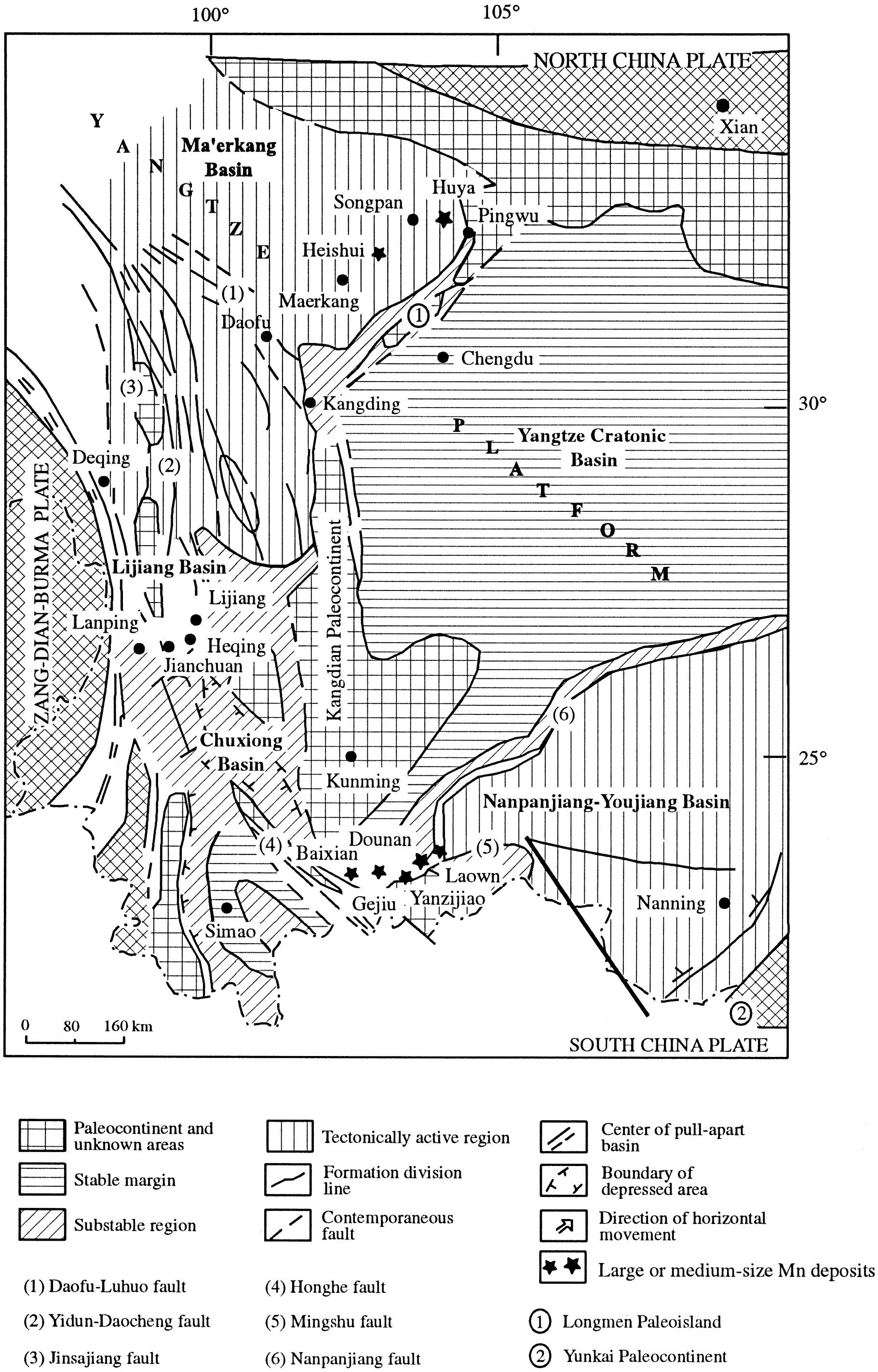

Fig. 2. Paleogeographic map for the Middle–Late Triassic showing the Paleo-Tethyan tectonic region and western margin of the Yangtze Platform.

graphic maps of the study area, which revealed an overlooked basic fact. Using sequence stratigraphy, we show that all Mn deposits along the western margin of the Yangtze Platform were deposited in condensed sections (CS) during the Ladinian. The CS formed at the maximum flooding stage corresponding to type III cycle of sea-level change at the same time as late-stage incipient parting of the Tethys seaway (Meng and Ge, 1993).

2. Manganese characteristics and tectonic setting during the Ladinian

Tectonics in the study area were relatively complex during the Triassic. Sedimentary rocks occur successively as red, compound, terrigenous clastic rocks and carbonate deposits (Early Triassic); siliceous-carbonate flysch (Middle Triassic); volcanic-hybrid rocks (Middle and Late Triassic); and volcaniclastic–terrigenous clastic rocks and molasse (Late Triassic), a succession that reflects deposition at an active continental margin evolving into a passive margin as the basin was gradually infilled (Geological Bureau of Yunnan, 1990). During the Ladinian, Carnian, and possibly the Norian, the area of study underwent two small late-stage spreading events due to extension of the Tethyan ocean in the west; which contrasted with the dramatically expanding Early Permian seaway. Consequently, a predominantly intrabasinal sedimentary source developed, characteristic of a divergent basin.

Convergent and divergent depositional systems coexisted laterally, which characterized the study area during the Ladinian; deposition occurred in a tectonically unstable area near formation of oceanic crust to the west which gave way to deposition in a substable (moderately tectonically and volcanically active region) environment near continental crust to the east. Deposits of the former environment consist predominantly of hybrid-type mafic volcanic rocks and island-arc volcanic, terrigenous, and carbonate rocks, while deposits of the latter consist predominantly of reef carbonate and euxinic carbonates. The Nanpanjiang, Ma’erkang, and Lijiang Basins, which contain numerous Dounan-type Mn deposits, lie at the inner margin of the Yangtze Platform near the transition to continental crust.

2.1. Basin framework: Early Triassic western margin of the Yangtze Platform

During the Early Triassic, the Longmen paleo-island and the Kangdian paleocontinent became barriers between the upper Yangtze epicontinental sea and the Tethyan ocean to the west (Fig. 1). Western Sichuan and Yunnan experienced sedimentation in a tectonically active region, indicating a convergent basin. Rao et al. (1985) and Rao (1990) determined that deposition of Upper Triassic and Middle Triassic strata did not occur in the areas of Songpan, Daofu, Ma’erkang, and others. The Zagashan Formation (Ladinian) directly overlies the Permian Sandaoqiao Formation (Fig. 3), suggesting that the Ma’erkang Basin basement, situated at the northern Daofu–Luhuo fault, was uplifted during the Early Triassic. Similarly, in Deqing–Simao, western Yunnan, the Middle Triassic Shanglan Formation disconformably overlies the upper Permian Sifudang Formation. This indicates that a large area in western Yunnan had been uplifted and accreted to the Kangdian paleocontinent. Along the Jinshajiang fault zone, radiolarian assemblages, black shale, limestone, pillow basalts, and ultramafic dike swarms have been documented. Ultramafic rocks and rocks formed along a paleo-Benioff zone outcrop at the western Jinshajiang fault and extend southward. These indicate that plate subduction was associated with uplift of those areas.

The Nanpanjiang Basin became part of the Tethys Sea during the Permian. In the Early Triassic, convergence occurred on the western side of the Honghe fault, forming a foreland basin closed to the west. Topography was high to the west and low to the east. The Indosinian and South China Plates converged northwestward simultaneously while the North Vietnam and Yunkai paleocontinents began to be uplifted. These led to a change in the depositional system from intrabasinal-sourced sedimentation in a substable environment to extrabasinal-sourced terrigenous sedimentation in a tectonically active environment.

2.2. Ladinian deposition and structural setting of enriched manganese basins

The Songpan–Ma’erkang area subsided dramatically during the Ladinian (Fig. 2). The Ma’erkang

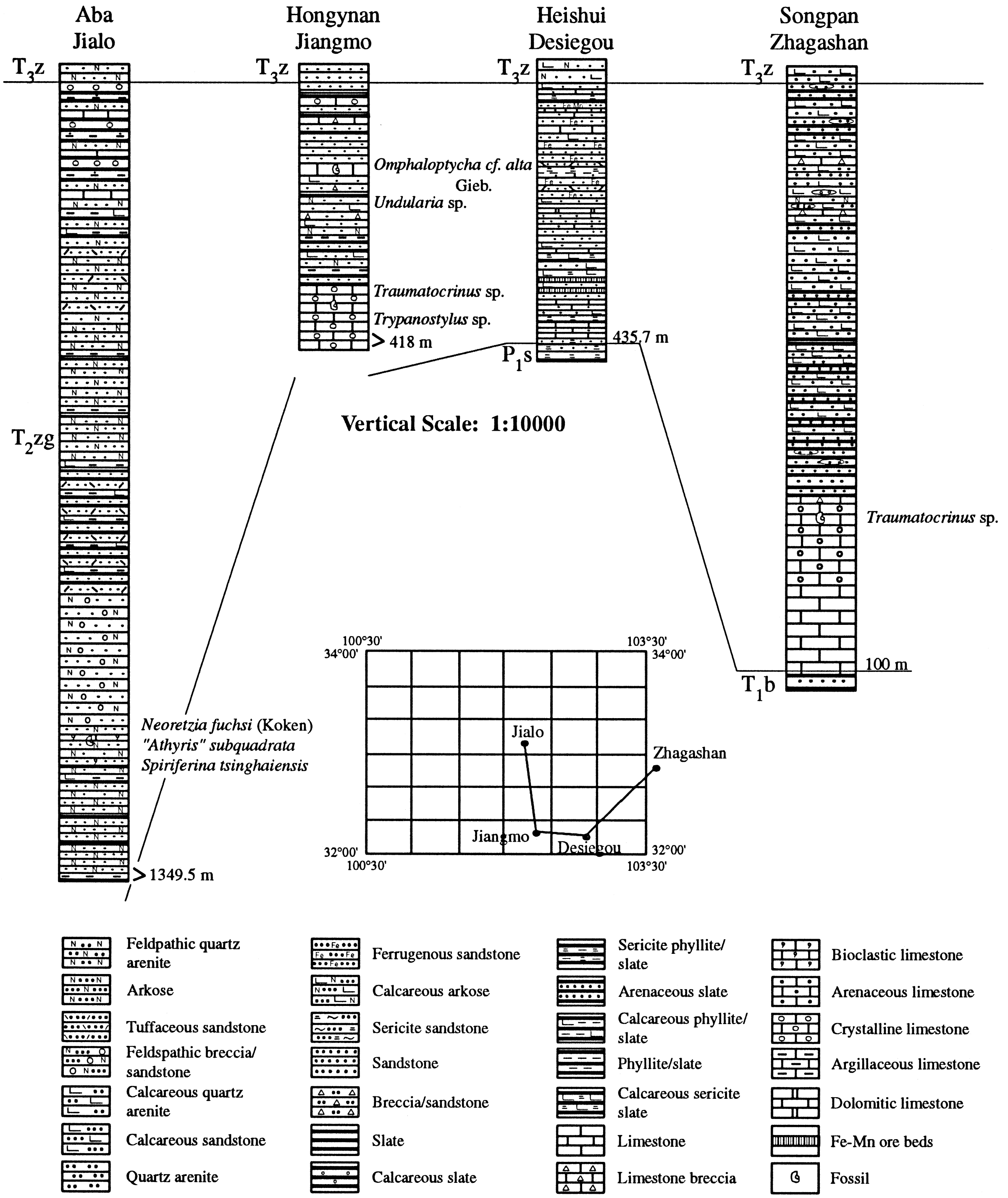

Fig. 3. Stratigraphic sections of the Middle Triassic Zagashan Formation (T2zg) in the Songpan–Ma'erkang area; P_1s = Lower Permian Sandaoqiao Formation, T_1b = Lower Triassic Bozigou Formation, T_3z = Upper Triassic Zagulao Formation.

Basin began to accommodate sediments after a long period of uplift. The Qinling seaway to the north had filled and was connected to the North China Plate. A thick section of Upper Triassic flysch (more than 5000 m) deposited in the north overlies the Zagashan Formation.

The Zagashan Formation consists of mixed carbonates associated with silty, fine-grained clastic sedimentary rocks that reflect the inadequate supply of terrigenous sediment during the early phase of basin subsidence. The locus of pull-apart tectonics (extensional basins) initiated during the Ladinian was situated near the Daofu–Luhuo fault in the southwest part of the basin. In that area, outcrops of melange containing carbonate and volcanic olistostromes occur. During the Carnian, there was very active volcanism along the Yidun–Daocheng fault. Volcanic rock (more than 2000 m thick) compositions changed from picrite basalt in the early phase to neutral acid volcanic and volcaniclastic rocks during the late phase. Sandstones and siltstones, jasperite, and radiolarian chert occur as intercalated beds within the volcanic sequence. As a result, the Ma'erkang Basin once again became a compound foreland arc–back arc convergent basin during the Late Triassic.

The Nanpanjiang Basin became part of the Tethyan sea during the Ladinian. Influenced by Tethyan spreading to the west, the western Yunnan area west of the Honghe fault was extended and subsided again. During the Anisian, the main body of the Yangtze Platform was dextrally sheared and moved northward. This caused the simultaneous faulting and extension along the NE- and ENE-trending Nanpanjiang and Mingshu Faults. Consequently, the Nanpanjiang Basin became connected with other basins to the west. Intrabasinal deposition of the main carbonate sequence developed along the depressed area during the Ladinian. Because of terrigenous replenishment from the Northern Vietnam and Yunkai paleocontinents, interbedded carbonate and terrigenous flysch sediments formed to the west and near the Youjiang Basin. Dounan-type Mn deposits developed in that kind of deep-water platform depression (e.g., Baixian deposit) and simultaneously on the basin slope and floor controlled by pull-apart basins along the Mingshu Fault (e.g., the Dounan, Yanzhijiao, and Laowu deposits).

It is not known whether the Lijiang Basin of northwest Yunnan contains strata of Ladinian age. The Beiya Formation of Middle Triassic age was originally assigned to the Anisian stage, based on regional geological studies in Yunnan (Geological Bureau of Yunnan, 1990). Strata between the uppermost Beiya Formation and the Upper Triassic Zhongwo Formation alternate transitionally and successively. The Beiya Formation was divided into upper and lower members based on the regional geological map of the Heqing area at a 1/200,000 scale. Mn ore occurrences and associated Mn-rich limestone occur extensively at the base of the upper member. If the Ladinian strata are missing from the Lijiang Basin, they stratigraphically would have occurred just below the Mn-rich limestone. So, here we correlate the lower member of the Beiya Formation with the Gejiu Formation (Anisian) of southwestern Yunnan and assign the upper member to the Ladinian. Consequently, Mn-bearing strata at the base of the lower member of the Beiya Formation, and the Mn ore bed confined to the Zagashan Formation in northwest Sichuan and to the Falang Formation in southeast Yunnan are thought to be coeval. This is consistent with the regional and inferred basin tectonic evolution of the study area.

3. Sequence stratigraphy and sedimentary facies of manganese-bearing deposits

3.1. Sequence analysis of the Ladinian deposits

Sedimentary sets formed during the Ladinian comprise a sequence unit that corresponds to the third-order cycle of sea-level change. Based on the above-mentioned correlations of Ladinian-age rocks, the following results can be ascertained.

The disconformity surface between the Falang Formation and the overlying Gejiu Formation of southeast Yunnan corresponds to the lowermost unconformity of the sequence. In the Dounan ore district, shallow-shelf carbonate and fine-grained clastic rocks were deposited on a marginal shoal that developed between the time of that sequence and the lower Mn-bed surface.

The member hosting the ore beds is a CS that consists predominantly of Mn ore beds with oolitic, oncolitic, grit, bioclastic, or microcrystalline-colloform textures, associated with similar textures in the host limestone. Siltstone, pelitic siltstone, and graded deposits penetrated the ore section as the result of fluid-escape channels initiated by loading from storms. Textures and compositional characteristics of the Mn ore beds and associated limestone indicate that they were originally deposited under quiet-water conditions when the basin was under compensated and were later modified by currents during transport to the shelf. In the Baixian ore district, situated in the same area as the Dounan deposits, dolostone and Ca-rich dolostone (more than 200 m thick) occur between the bottom of the Falang Formation up section to the base of the Mn ore bed. Dolostone beds gradually thin up section. Wavy layers of interbedded dolostone and siliciclastic rocks occur in the upper part of the dolostone section and represent dolomitized euxinic basin rocks of the carbonate platform, which correspond to the transgressive system tract (TST) in sequence stratigraphy. Thin terrigenous clastic beds occur in the hanging wall and footwall of the Baixian Mn ore, resulting from deposition by low-velocity currents, and these beds are thought to be coeval with the Mn ores in the Dounan–Laowu area. The relationship between the upper surface of the Falang Formation in Dounan and the Niaoge Formation of Upper Triassic age in Baixian are successively transitional and disconformable. This indicates that the later onlap highland system tract (HST) is separated by a type-II unconformity. The HST between the top of the CS and the upper surface of the sequence consists of several normal-graded rhythmic sets with fine- to medium-grained quartzose sandstone and siltstone. Between them occur low-angle cross bedding, lenticular bedding, and convolute bedding. Sedimentary structures such as graded bedding and slump deformation are often present in the carbonate rocks. The corresponding strata in the Baixian ore district occur predominantly as a set of thinner beds, mainly of carbonate rocks, with fine-grained clastic rocks only in the upper part.

The sequence structure of the Ladinian deposits of northwest Sichuan is not complete compared with that of southeastern Yunnan. The TST in the lower part of the Zagashan Formation is not so widespread. The surface of the Mn ore bed, as with the CS member, is superposed on the unconformity of the overlying sequence. These resulted from sediment replenishment at a relatively low rate while the base of the Ma'erkang Basin subsided significantly after a long period of erosion. Coeval Mn ores include the Huya-type Fe–Mn deposits located near Pingwu–Songpan, and the Si-rich Mn deposits located near Heishui, as well as the ore-bearing beds of the Dounan and Baixian deposits. The Huya-type Fe–Mn ore beds contain relatively abundant collophane, and the Si content of the Heishui Mn ore is as high as 35.2%. Mn, Si, and P are abundant in CS member ores, which were deposited by low-velocity currents. Upper Triassic rocks (turbidites of the Zagunao Formation) unconformably overlie Ladinian rocks. Between the Upper Triassic sequence and the Mn ore beds occurs a set of cyclic sediments composed of fine-grained quartzose sandstone, feldspathic–quartzose siltstone, and microcrystalline limestone, which resulted from lateral accretion on the shelf.

The above analysis shows that the Dounan-type Mn deposits in different areas of the Yangtze Platform's western margin are coeval, corresponding to maximum flooding of the Type-III eustatic cycle of global sea-level. The ores correspond to deposition on the maximum flooding surface (mfs CS) and is an obvious marker to identify the CS member. The environment and depositional controls can be inferred from sequence analysis.

3.2. Sedimentary facies and characteristics of the Mn-bearing stage

Differences in ore-body size, orientation, and composition depend on the degree of development of the sedimentary successions. The source of sediments, depositional environment, and degree of energy equilibrium are three important factors used to identify the Mn-bearing sedimentary-facies type. There are four kinds of Mn-bearing sedimentary facies mentioned below:

(1) *Dolomite-rich rocks* are typified by the Baixian Mn deposit. They were deposited in a local carbonate–evaporite basin on the platform. The source of sediments was mainly intrabasinal. The degree of energy equilibrium produced an assemblage of low-velocity current deposits with an uncompensated-sediment supply.

(2) *Glauconite-bearing oolitic rocks* are typified by the Dounan deposit. The depositional environment was the foot of the basin slope with sediment sources of mixed allochthonous carbonate and terrigenous clastics.

(3) *Phosphate- and iron-rich rocks* are typified by the Huya Fe–Mn deposit. The depositional environment was a sandy–silty shallow-water shelf depression, with P and Mn derived from oceanic upwelling and clay minerals and part of the Fe from the paleocontinent. The P content in the ore-bearing bed is up to 0.35%, occurring as collophane, which correlates with Fe content. Because of the short distance from the paleocontinent, the terrigenous compensation rate was relatively higher than that in other areas. Thus, there was little fractionation of Fe, Mn, and P, thereby lessening the industrial usefulness of the ore.

(4) *Si-rich rocks* are typified by the Heishui deposit. The depositional environment was a deep-water shelf depression of mixed carbonate and sandy–silty sediment with weak terrigenous input. Mn may have been derived from colloidal–chemical deposition and silica possibly from biogenic silica, both with low- to medium-depositional rates. Hydrothermal alteration during diagenesis and metamorphism caused changes in the mineral phases. The degree of metamorphism reached greenschist facies.

Types 1 and 2 deposits occur in the Nanpanjiang Basin. Type 1 deposits were distributed along a stable margin, whereas type 2 deposits were located in the transition zone from the center to the margin of the basin, with deep water and relatively subdued topography. Types 3 and 4 deposits are mainly present in the Ma'erkang Basin system. Water depths for type 4 sediments were deeper than those for type 3 sediments. The type 4 environment permitted formation of high-quality Mn ore beds, as determined by the source of sediment supply and the rate of deposition.

4. Geological characteristics of typical deposits

Geological characteristics are quite similar among the various deposits in the following aspects outlined below:

(1) Multiple persistent ore beds are typical. Deposits of Baixian, Dounan, Yanzijiao, and Laowu, commonly situated in the Nanpanjiang Basin system, consist of compound ore beds, with upper and lower ore beds correlatable from place to place (Fig. 4). An ENE-trending metallogenic belt was formed extending west of Baixian to Yanzijiao and continuing east to Laowu. This metallogenic belt was controlled by the synchronous ENE-trending Mingshu Fault, whose wall-rocks change from mainly carbonate rocks in the west to mainly carbonate-terrigenous clastic rocks in the east. Ore beds are often distributed along both limbs of a syncline. Up to five major ore-bearing beds occur in the Heishui Mn deposit, with more than 20 individual ore layers. Ore body lengths range from 50 to 600 m. Similar to the Dounan deposit, the ore beds of the Heishui deposit are distributed along both limbs of a syncline and are thicker at the core of the fold.

(2) All ore districts are in the eastern part of the basin. Imbricate arrangement of ore bodies in the Dounan ore district indicates eastward migration of the depocenter. The Mn ore body intersects the ore host beds at a 40° angle, laterally plunging eastward, which suggests that the bottom currents weakened eastward. The main ore body of the Heishui ore district consists of several secondary ore beds composed of lenses in an imbricate arrangement.

(3) The hanging wall and/or footwall of the ore bodies commonly consist of carbonate rocks, associated with terrigenous beds. Ores generally contain high-silica contents (> 25%; except at Huya). These compositional characteristics indicate that at the time of ore formation, the sediment–water interface may have been near the CCD.

(4) The primary Mn oxide, carbonate, and silicate minerals commonly occur as rhythmic layers denoting fluctuating Eh and oxygen fugacity. These ores commonly form high-grade Mn deposits. This kind of ore with rhythmically banded mineral phases is typical of the Dounan Mn deposit. Grade I (> 35% Mn) braunite ores are distributed in the center of the ore body while grades II (25–35% Mn) and III (18–25% Mn) transitional braunite–rhodochrosite ores are distributed in an inner ring around the center; Mn-calcite bearing low-grade ores and rocks are distributed in an outer ring. In the Heishui ore district, similar to the Dounan deposit, braunite-ore beds occur stratigraphically in the middle bed; layered braunite–rhodochrosite beds and low-grade ore

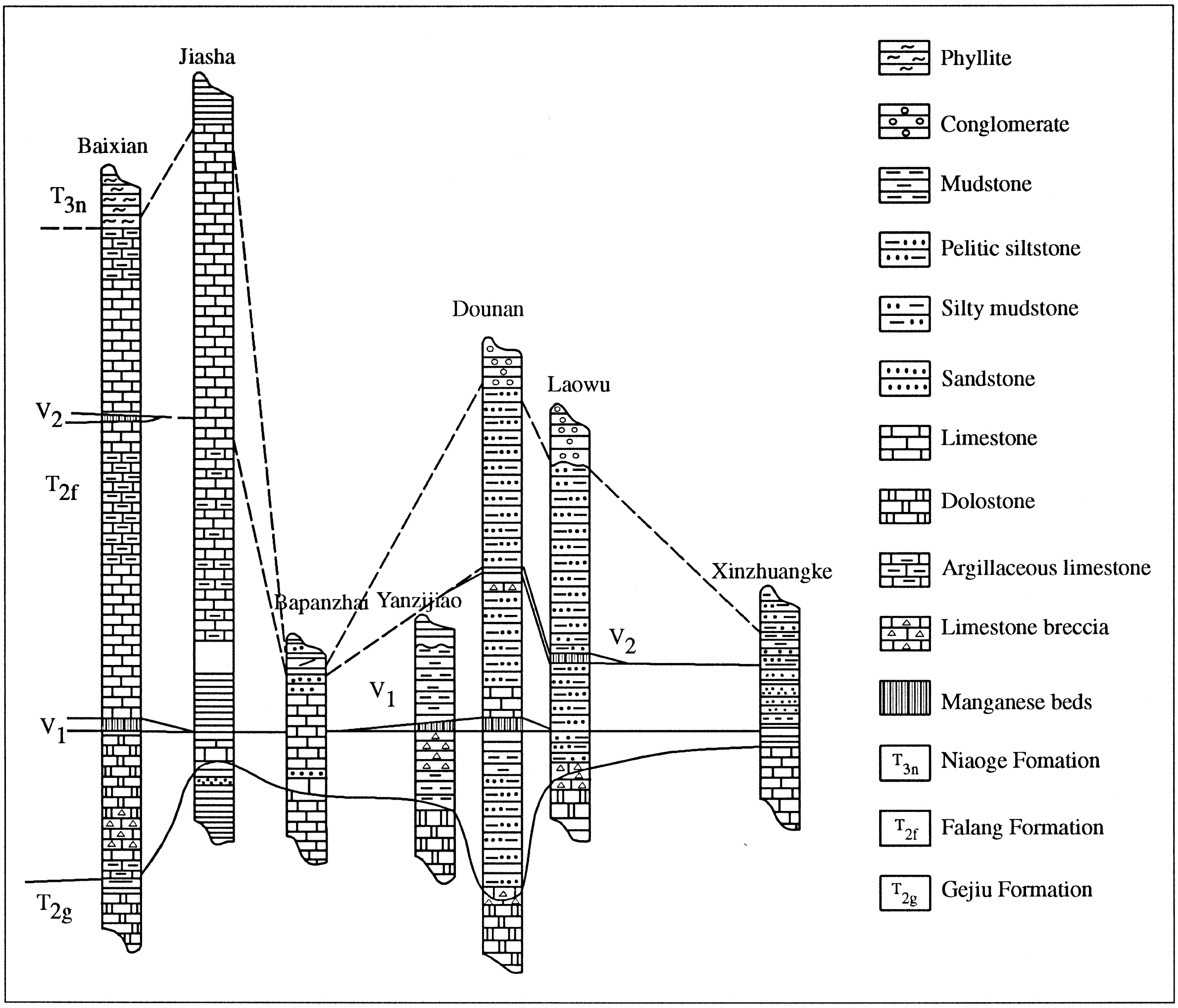

Fig. 4. Strata correlation map of the Middle Triassic Falang Formation of southeastern Yunnan; V1 is the lower Mn ore bed and V2 is the upper Mn ore bed.

beds composed predominantly of Mn calcite are distributed cyclically, commonly associated with metamorphic-generated silicate minerals such as spessartite, rhodonite, piemontite, and others.

5. Genetic model

The conventional view of the origin of Dounan-type Mn deposits was generally the chemical and mechanical differentiation of Mn in the littoral shallow-sea part of the continental margin where sediments from the paleocontinent and paleo-islands accumulated. In line with ore-bearing wall-rock types and ore compositions, many origins for the various deposits have been put forward, such as for the Dounan-type (narrow sense), Baixian-type, and Huya-type deposits. But as was previously stated, those models do not take into account the relationship of the structural setting of the basin to the timing of formation and depositional mechanisms. Based on the paleo-Tethyan sedimentology of Mn deposits of the western margin of the Yangtze Platform, Liu (1996) put forward four main conditions that controlled metallogenesis including the Dounan-type Mn deposits of the study area: Basin control (pull-apart basin), temporal control (CS), Mn source (mantle-sourced juvenile water), and deep-sea deposition (below the CCD). The characteristics of basin control and temporal control have been systematically discussed above and Mn source and concentration in seawater are discussed next.

The Mn source (Fig. 5) was located in the area of abundant mixed volcanic–terrigenous deposits in the western part of the basin (Liu, 1990). Mn may have been transported along the seafloor by bottom currents that moved along a pull-apart basin main-branch fault that contributed Mn and other elements possibly derived from degassing of the mantle and volcanic activity (Lisitzin et al., 1985; Gross, 1990). Limited isotope data of Mn ore from the Baixian and

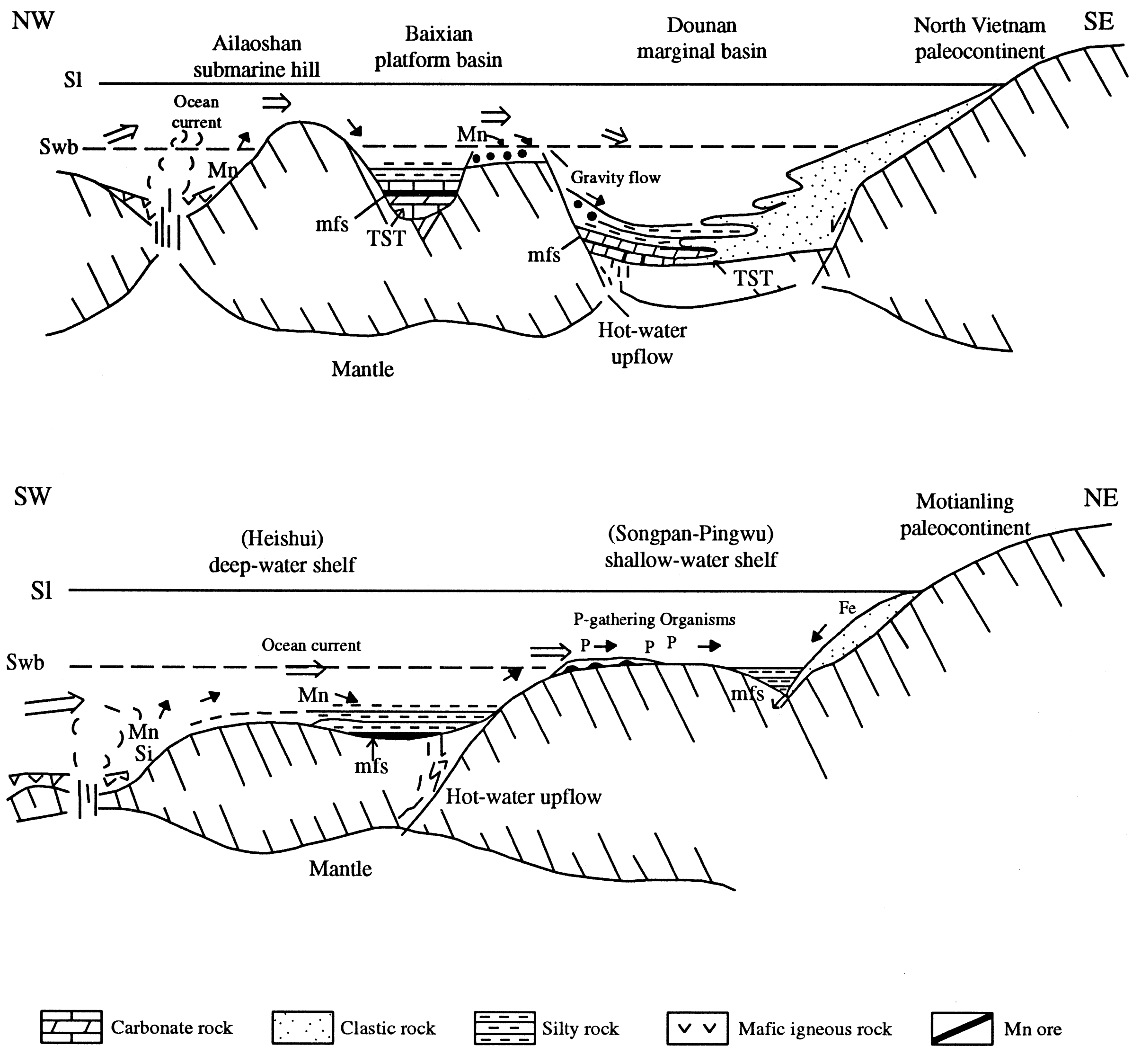

Fig. 5. Ocean-current Mn-enrichment model of Dounan-type Mn deposits; mfs = maximum flooding surface; Sl = sea level; Swb = surface of windstorm base; TST = transgressive system tract.

Dounan ore districts (Table 1) show that $\delta^{13}C_{PDB}$ values of Mn-carbonates from the ore and Mn-bearing carbonate rocks of the Dounan ore district vary from −6.1‰ to −7.9‰ and the Baixian Mn-carbonate ores have $\delta^{13}C_{PDB}$ values as negative as −11.6‰. These isotopic values indicate that part of the carbon for the primary carbonate ore was derived from the degradation of organic matter (Hein and Koski, 1987; Okita et al., 1988), but more than 50% of it was probably derived from seawater bicarbonate. The isotopic data for deposits from the Dounan ore district are also consistent with the derivation of some CO_2 from volcanic sources and thus the isotopic composition cannot distinguish between volcanic, organic matter, and seawater sources. The $\delta^{13}C_{PDB}$ values of the sedimentary carbonate-host rocks range from −3.0‰ to +3.4‰, close to the range of seawater bicarbonate values (Chen and Chen, 1983).

Many common geological characteristics were noted from comparisons of Mn deposits from different areas, which indicates that the Mn-depositing fluid, predominantly seawater, had similar characteristics. Bottom currents that carried the metals flowed from west to east (Fig. 5) and the current energy decreased when it encountered the slope in the eastern part of the basin near the boundary with continental crust. Metals from the western source area formed proto-ore beds and medium- or low-grade ores when they encountered the appropriate Eh–pH conditions. This stage of ocean-current transport coincided with the maximum flooding stage of the sea-level cycle during the Ladinian. Seasonal ocean currents and lower-cycles of sea-level change caused the multiple bed characteristic of the ores. Oolitic ores of Dounan-type Mn deposits formed when particulate Mn sediment or sub-solid Mn-carbonate were transformed into particles during storms and associated ocean currents and then by gravity sliding in the opposite direction of current motion; this interpretation is consistent with the character of the imbricate arrangement and laterally eastward plunging ore bodies.

The origin of the P-rich Huya-type Fe–Mn ore is closely tied to ocean currents. It was generally thought that P concentration resulted from absorption of dispersed P particles by organic matter (such as algae) in the photic zone. Along Songpan–Pingwu, eastern Ma'erkang Basin, the shallow-shelf seafloor deepened gently. Furthermore, because only a small amount of terrigenous sediment was deposited at the maximum flooding stage, during oceanic upwelling, phosphates were concentrated by organic matter and formed phosphatic sediments. Those sediments were deposited with Fe–Mn sediments after they were scoured and transported to deeper water areas during storm events.

Mn-bearing hydrothermal fluids may have ascended along faults and then transported by bottom currents. That Mn may have reformed and concentrated the ore body that had formed earlier. This kind of hydrothermal mineralization can produce banding of the type seen in the ores. For example, in the Dounan ore district, the main ore body predominantly consists of braunite, while the ore texture indicates grain-flow deposition of Mn-carbonate oolites. Mn-carbonate was transformed to Mn oxide, which can be interpreted as hydrothermal alteration during syngenesis–diagenesis, or alternatively as early diagenetic oxidation of the Mn-carbonates due to fluctuations in redox conditions. The hydrothermal or diagenetic processes may have caused the proto-ore and low-grade ore that formed at the depositional stage to be transformed into medium- or high-grade industrial ores.

Table 1
Carbon isotopic composition of carbonate rocks and ores. Refs.: 1 = Liu (1996); 2 = Renfu Liu, unpublished data, 1994

Location	Sample type	Range $\delta^{13}C_{PDB}$ (‰)	Mean $\delta^{13}C_{PDB}$ (‰)	No. of samples	Refs.
Dounan	Mn carbonate	−6.9 to −7.9	–	3	1
Dounan	Limestone	–	−3.0	7	1
Dounan	Mn dolomite	–	−6.1	2	2
Baixian	Mn carbonate	–	−11.6	5	1
Baixian	Limestone	+3.4 to −1.8	–	6	1
Tangdian	Mn calcite	–	−6.3	1	2

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