SCHLUSSBERICHT

'MONSOON DYNAMICS AND ARIDIFICATION - THE CLIMATE ARCHIVE QAIDAM'

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1. AIMS AND WORKING PROCEDURE

1.1 Scientific and economic background

The Tibetan plateau and its surrounding regions are of outstanding scientific, economic and socio-political importance. Long-term changes in environmental conditions (evolution of the monsoon system, aridification and water cycle) and the emergence of natural resources (mineral deposits and hydrocarbons) in Central Asia are directly linked with the formation and uplift of the plateau. Yet, also when looking at much smaller time scales, such as the recent episode of global warming, the Tibetan plateau is a "hotspot" for climate research, showing significantly elevated warming coupled with drastic changes in the hydrosphere and cryosphere. Therefore and considering that all major rivers in Asia - including the Yellow River, the Mekong and the Ganges - are fed by Tibet´s glaciers, it becomes clear that environmental changes in the plateau region have major implications, affecting almost a third of the world´s population. In order to develop sustainable options of action to address issues related to this topic, it is crucial to acquire a better understanding of the mechanisms, which control the climate system in the Asiatic monsoon region.

The proposal is built upon the scientific findings and the logistics that were acquired within the framework of the DFG priority program TiP "Tibetan Plateau: Formation - Climate - Ecosystems", and the BMBF program CAME "Central Asia and Tibet: Monsoon dynamics and geo-ecosystems". As a central element of TiP, the project "Late Neogene environmental evolution of the Tibetan plateau recorded in long-term lacustrine archives" is further closely linked to the BMBF project 03G0705A by two joint Sino-German drilling campaigns (SG-1/SG-1B) in the western Qaidam basin. Thereby, optimal synergy effects could be developed: The BMBF project significantly contributed (in equal shares with the Chinese cooperation partners) to the realization and funding of the drilling campaigns, whereas the TiP program specifically focused on the measurement and interpretation of paleoclimate proxies.

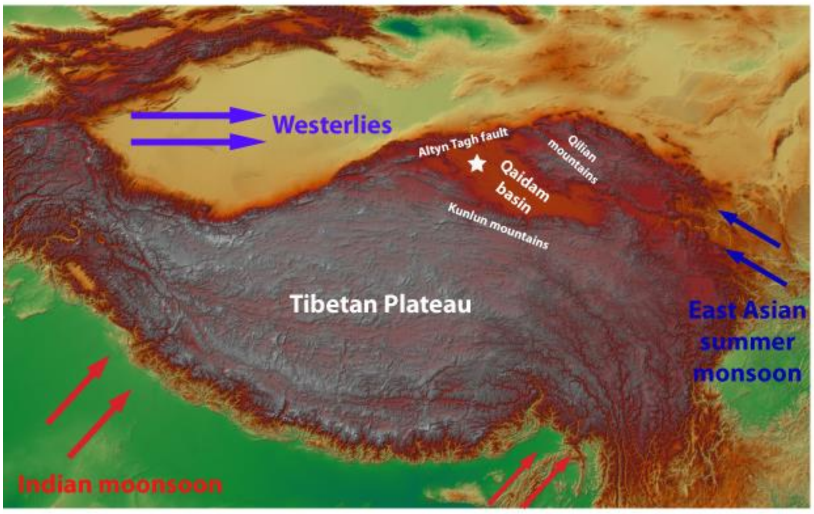


Fig. 1: Topographic map of Tibetan plateau and the surrounding areas. (Paleo-) wind directions affecting the Qaidam basin are indicated by arrows. The star indicates the location of the drilling sites in the Qaidam basin.

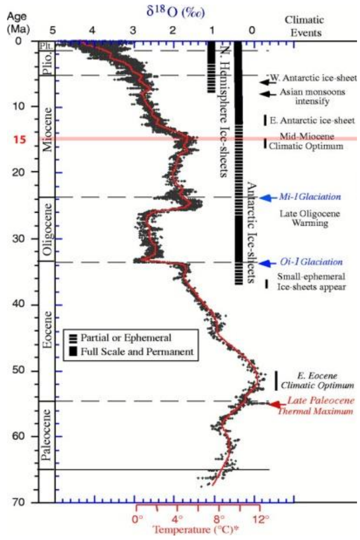


Fig. 2: Global deep sea oxygen isotope record derived from benthic foraminifera (modified from Zachos et al., 2001).

This project was designed as feasibility study (pilot project) for a future drilling campaign in the western Qaidam basin. The basin is located at the northeastern margin of the Tibetan plateau (Figure 1), comprising one of the world´s thickest Cenozoic sequences of lacustrine sediments. As these lithologies were continuously deposited in closed-basin conditions from Eocene to Pleistocene, they provide a potentially excellent archive for a high-resolution, multiparameter analysis of the paleoclimate. Results acquired from drilling campaigns to depths of 990 m in the Chahansilatu sub-depression (SG-1) and 550 m in the Jianshan anticline (SG-1B) are very encouraging in this respect (Wang et al., 2012; Zhang et al., 2012; Herb et al., in review) but limited to a maximum age of 2.8 and 6.2 million years (Ma), respectively. This time range, however, is too short at the bottom end to unravel the development of the monsoon system and progressing aridification in Central Asia. In particular, the key question of how the uplift of the Tibetan plateau and global cooling at 14 Ma - as indicated by the ^{18}O record in marine sediments (Figure 2) - influenced the formation of an aride zone in Central Asia cannot be addressed. A further drilling project, possibly combined with surface sections and results from already existing cores, is hence mandatory to cover the critical period from ca. 15 Ma to sub-recent.

1.2 Concrete aims of this study

In this pilot study we assess whether and if in what way it is possible to recover a continuous drill core that covers the time frame of the last 15 million years. We weigh assets and drawbacks of potential alternatives, including costs, define the reachable goals and ultimately suggest the most promising locality for a future drilling site in the western Qaidam basin. All available information, ranging from field observations over seismic sections to different sets of geophysical logging data, are therefore combined and evaluated. In the run-up to this pilot study, the following scenarios were identified as realistic options to reach the aforementioned goal of a continuous sequence to 15 Ma:

- Option 1: Drilling into the center of the Dafengshan anticline and combining the results with existing data from SG-1B. There is, however, the possibility that the top of the Dafengshan anticline is younger than the bottom end of SG-1B. In this case, an additional short drilling core in the crest of the Dafengshan anticline would be required to fill the time gap. Alternatively, surface sections over the Dafengshan anticline could fulfill the same purpose.

- Option 2: Drilling into the Jianshan anticline by deepening of SG-1B. The upper 720 m could, but do not necessarily have to be re-sampled, as they are already available from SG-1B.

- Option 3: Continuous drilling into the horizontal layers within the Chahansilatu sub-depression. In order to reduce costs, the uppermost 940 m, which were already sampled during the drilling of SG-1, could thereby be intersected without taking cores.

Finally, it should be noted that all options would make use of the already existing results from SG-1, in order to cover the most recent part of the sedimentary sequence.

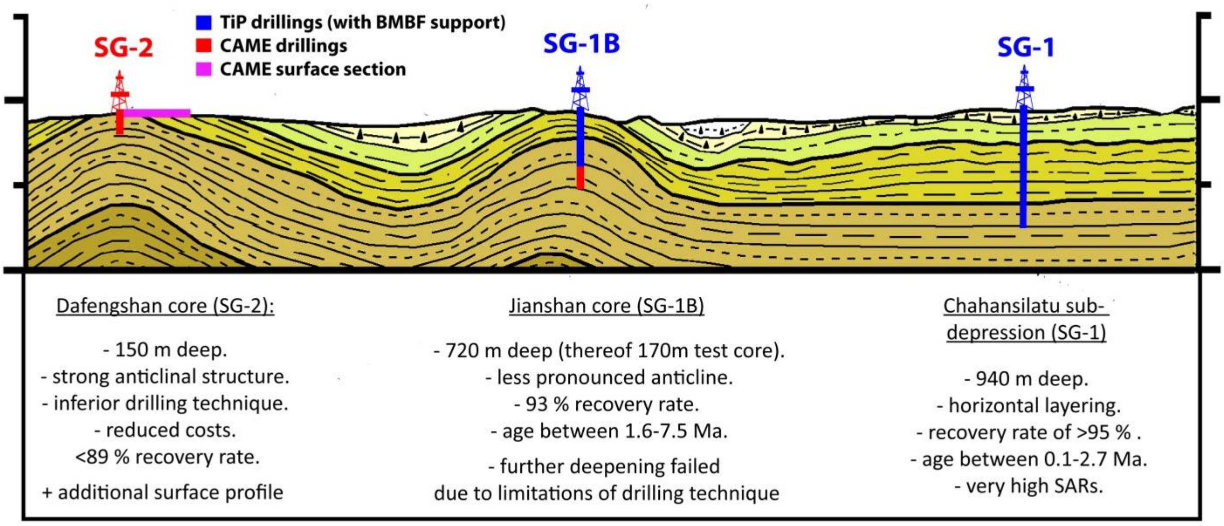


Fig. 3: Overview of drilling cores that were retrieved in the framework of TiP and CAME. Additional information include depth, recovery rate, tectonic setting and age interval (if known) of the cores. The drilling locations of the existing sites likewise represent the target areas for a potential future drilling project to 15 Ma (modified from Zhang et al. in review)

The most crucial findings constitute of pollen analyses, interpretation of sediment structures and magnetostratigraphic investigations from SG-1 / SG-1B and two relatively short test drilling cores in the Jianshan- and Dafengshan anticlines of 170 m and 150 m length, respectively. The drilling and investigation of additional test cores as well as the sampling along a surface section in the Dafengshan anticline were conducted in the framework of this pilot study and were required for the following reasons:

- To find out whether the sediment accumulation rate in the Jianshan anticline significantly decreases with larger depths as indicated in the lower part of the SG-1B core. This is essential in order to estimate what depth has to be penetrated to reach 15 million years.

- To elaborate whether the lithology in the strongly pronounced Dafengshan anticline shows signs of internal disturbances in the sedimentary fabric. Further, indications for hiatuses or partial recurrences of subsequences in the sedimentary record have to be diligently considered, since a discontinuous timeline along the core would fundamentally jeopardize the overall success chances of a future project. Secondly, if these questions yield affirmative findings to date the core sequence using magnetostratigraphy.

- To test if surface sections provide a feasible option to bridge a potential time gap between SG1 / SG-1B and the future drilling core. For this purpose, a suitable location for a surface section has to be found and an about 1 m deep trench has to be dug. Sediment samples therefrom have to be investigated in terms of the pollen preservation degree. Further, it has to be determined, whether weathering effects near the surface negatively influence the magnetic properties of the rocks or if magnetostratigraphy works fine.

1.3 Work progress and cooperation with third-parties

This pilot project was conducted in a framework of Sino-German research cooperation with shared responsibilities and an equal distribution of tasks. It was further envisaged as a highly integrated approach, in which data and knowledge from different fields of geosciences are combined and evaluated in order to determine the best course of action for a future drilling project to 15 Ma. A close collaboration and continuous knowledge exchange between Chinese and German project partners paired with the obtaining of external expert opinions were thus crucial for the henceforth presented successful interdisciplinary working process (Figure 4).

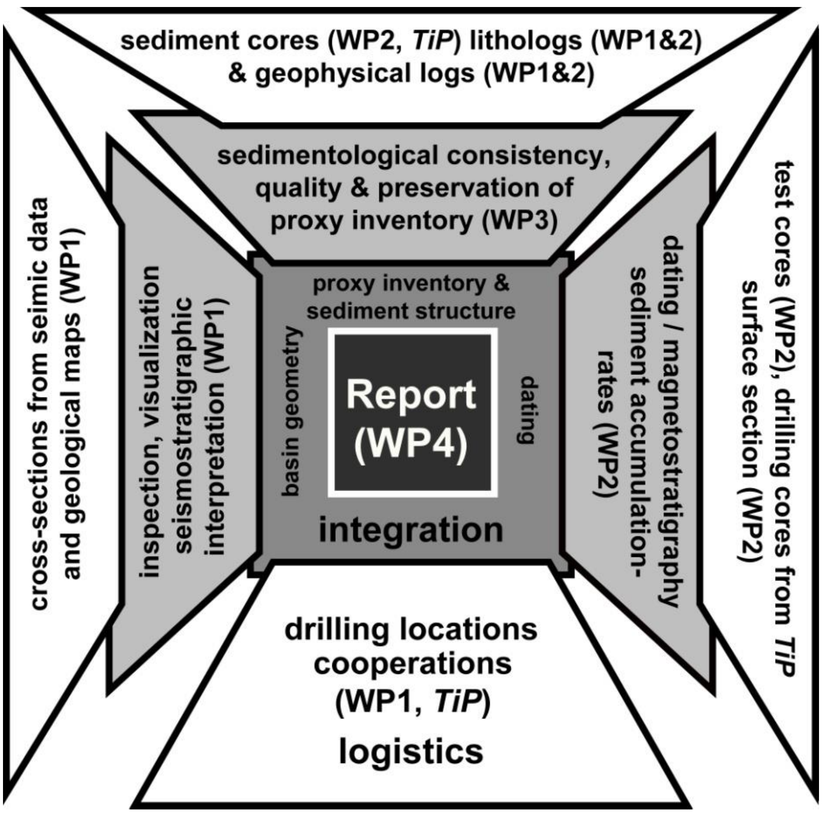


Fig.4: Schematic overview of the different work packages (WP) and how they are interlinked with each other and with the results, which are available from TiP.

Directly following the official approval of the project, a comprehensive collection of seismic cross-sections and geophysical logging data was provided by the Chinese oil company PetroChina through our cooperation partners from the Institute of Tibetan Plateau research (ITP). It is stressed, that the acquisition of such comprehensive datasets, which are usually confidential, was only possible due to year-long good contacts between Prof. Fang (ITP) and PetroChina and the mutual basis of trust between Chinese and German research groups.

Fig. 5: View on the borehole casing of SG-1B. After the initial drilling campaign to 550 m, the borehole was kept open and intact in order to allow a later deepening as part of this pilot study. Eventually, a final depth of 723 m was reached.

Further and also still in a very early stage of the project, detailed geological maps of the Qaidam Basin and the surrounding catchment area became available. On this basis and combined with the knowledge of the basin geometry, as derived from seismic cross-sections, suitable locations for a test drilling site and a surface section in the Dafengshan anticline could be identified.

Fig.6: View on the veiled drilling rig in the Jianshan anticline during winter times.

The subsequent drilling and retrieval of the Jianshan- and Dafengshan test cores as well as the digging of a surface section (Figure 7) was organized and conducted under the supervision of the Institute of Tibetan Plateau Research:

The <u>test core in the Jianshan anticline</u> was realized as deepening of SG-1B from originally 550 m to a final depth of 723 m. Such an approach was possible, since SG-1B was appropriately cased following the initial drilling campaign (BMBF program: 03G0705A), allowing the borehole to stay open and intact (Figure 5). However, due to limitations of the drilling instrumentation, the intended depth of 850 m could despite multiple efforts from the drilling company not be reached. The problem could not be foreseen, as with the same rig, a depth of 940 m was reached in the drilling of SG-1. Nevertheless, the retrieved 170 m long sequence was still sufficiently long to tackle all relevant questions, neither affecting the aims of the project nor its prospects of success. Beyond that, the recovery rate was excellent (93%).

Fig. 7: Surface section in form of a 1 m deep and 5 km long trench over the crest of the Dafengshan anticline.

In the aftermath of the drilling campaign, the core was cut in two identical counterparts: One half remained in China and the other was shipped to Germany, where it is now appropriately stored in the core shed of the University of Tuebingen and has since been investigated in terms of palynology, magnetostratigraphy and sedimentology.

The sedimentological description was carried out in close cooperation with Prof. Thomas Aigner and the working group "sedimentology" from the University of Tuebingen. Sediment samples for pollen analyses were prepared and evaluated by Dr. Sonya Adamczyk at the University of Hohenheim. Magnetic measurements were conducted in the paleo-and rockmagnetic labs in Tübingen and could directly be incorporated in the running works of TiP concerning age dating and determination of the sediment accumulation rate of SG-1B.

The Dafengshan test core, henceforth also referred to as SG-2, was drilled into the center of the anticline structure. In order to account for a drastic increase in drilling prices during the field season 2012, it was decided to reduce the target depth from 200 m to 150 m. Two core segments with a length of 130 m and 38 m were retrieved. The longer core segment was taken continuously from the surface to a depth of 150 m, yielding a mean recovery rate of (≤90%). The far shorter, second core only comprises the uppermost 30 m and a further horizon at a depth of around 100 m, which were re-sampled in order to overcome the particularly poor recovery rate within these intervals in the main core.

The sampling and evaluation process for magnetostratigraphic and palynological investigations, as well as the description of the sedimentary fabric were conducted in an identical manner as for the Jianshan test core in order to allow optimal comparability. However, this time the sampling work was not conducted in Tuebingen, but directly in Lanzhou/China in the follow up of a field campaign to the Qaidam basin. A costly transport of the entire cores to Germany could therefore be avoided. For sedimentological expertise, in particular regarding the description and interpretation of sediment structures, a member of the working group sedimentology from the University of Tuebingen was again called in to accompany the work on site.

The surface section in the Dafengshan anticline (Figure 7) was realized as a roughly 1 m deep and 5 km long trench that was dug in an effort to retrieve unaltered samples. The profile runs in a north-south direction from the core of the anticline over its crest towards its southern margin, covering a stratigraphic thickness of altogether 350 m. The entire sampling process as well as subsequent lab work and measurements were conducted by members of the working group of Prof. Fang Xiaomin (ITP). All relevant aspects ranging from lithology over magnetostratigraphy to palynology were thereby thoroughly studied and findings were steadily forwarded to Tuebingen and could in this way be directly incorporated in this pilot study.

In the final stage, the cumulated findings from the two test cores and the surface section were combined with the already available outcome from TiP and the insights derived from seismic cross-sections and geophysical logs. The lithology and the proxy inventory of cores from different localities were thereby successfully evaluated in terms of their overall suitability as climate archive. Dating based on magnetostratigraphy and seismostratigraphic interpretations further provided the desired constraints of the to-be-expected ages and sediment accumulation rates. On this basis, estimates about the required drilling depth to reach 15 Ma could be made for all potential drilling sites and concrete expense budgets for the respective scenarios could accordingly be obtained from two Chinese drilling companies.

Recapitulatory, it can be said all major works related to this pilot study could be fulfilled according to the proposal. Open key questions could be addressed and the defined goals were fully accomplished. The proposed time schedule could also be met for the most part.

Merely the final integration and evaluation of the comprehensive datasets took more time as anticipated, since it required a very time consuming iterative approach of information exchange between China and Germany. In order to ensure that the integration process, as most crucial part of this pilot study, could be conducted in all necessary detail, the running time of the project was (cost-neutrally) extended by 3 months.

2. RELEVANT RESULTS FOR ASSESSMENT OF PERSPECTIVES

The lithology in all three locations (Jianshan anticline, Dafengshan anticline and Chahansilatu sub-depression) is quite similar and characterized by very fine grained lacustrine sediments of mainly mud- and siltstones that are interbedded with marl and / or massive carbonate congretions. The mudstones typically appear in different shades of grey, with some of them showing a slight hint towards green or blue. Sporadically, also thin, organic rich layers with an almost black color occur.

The top part of the Dafengshan test core poses an exception and has a light brown to ochre color. The core SG-1, and thereof in particular the uppermost part, is further characterized by meter thick white halite layers and gypsum beds. Further, it should be noted that material from any lithology and locality whatsoever show a reaction with HCl, implying significant concentrations of carbonate along the entire sequence.

The relative proximity of the individual drilling sites in regard to the huge distance to the basin margin suggests that the source area of the sediment is practically identical in all locations. A reconstruction of the (paleo-) basin bathymetry approved this assumption, as no indications for any internal barriers (-> paleohighs within the basin) could be revealed (Figure 8). Field observations further made clear that the Altyn Mountains (Figure 9) represent the only plausible source area for the sediments, which were deposited in the NW part of the Qaidam basin.

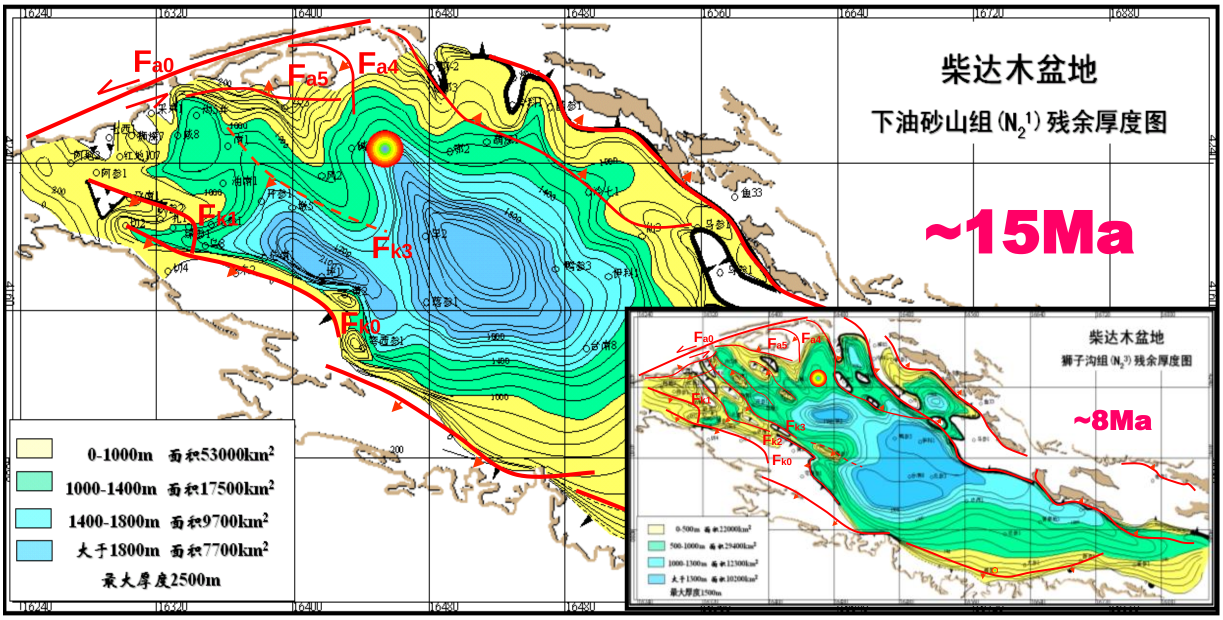


Fig. 8: 3-D dynamic evolution of the Qaidam basin as indicated by paleo-bathymetry isolines for the time slides of 15 Ma (big picture) and 8 Ma (small picture). An eastward shift of the depocenter is clearly indicated. The location of SG-1 is indicated by the rainbow-colored symbol. SG-1B and SG-2 are located close-by; several kilometers south-west of SG-1.

Fig. 9: View on the Altyn Mountains - the likely source area of the sediment deposits in the northwestern part of the Qaidam basin (where all of our drilling sites are located).

For a high-resolution climate reconstruction less eligible lithologies, such as conglomerates or very coarse grained sandstones are fortunately almost absent and only occur in form of two narrow horizons in the surface section of the Dafengshan anticline. From a lithological viewpoint, a primarily episodical and therefore discontinuous deposition during short term events can hence be ruled out.

Based on characteristic textures in the sedimentary fabric, the description and logging of the cores revealed a set of lithofacies that are characteristic for different depositional environments:

In SG-1, five lithofacies namely (1) gray-black laminated mudstone, (2) gray massive mudstone and siltstone, (3) bedded halite, (4) loose muddy halite, and (5) brownish-yellowish saliferous siltstone were recognized, representing (1) semi-deep fresh to semi-brackish lake, (2) shallow brackish lake, (3) perennial saline lake, (4) playa saline lake and (5) saline mudflat conditions, respectively (Wang et al., 2012). The sequence generally shows a coarsening upward trend in the grain size and an increase of evaporite layers towards younger ages, reflecting a progressing shrinkage and eventual termination of the Chahansilatu paleo-lake. Accelerations in the rate of lake shrinkage are observed at ca. 2.5 Ma, 2.2 Ma, 1.6 Ma, 1.2 Ma, 0.9 Ma, 0.6 Ma, and 0.1 Ma (Wang et al., 2012). Signs for a wind erosions as indicated by Kapp et al., (2011) were neither found in SG-1 nor in any of the other cores .

The lithostratigraphic description of the Dafengshan test core revealed a slightly different set of sedimentary facies but even more importantly it provides strong evidence for tectonically induced disturbances in the sedimentary fabric along much of the sequence.

A large part of the core consists of unconsolidated- and consolidated mudstones that are usually very homogeneous and show no or very little internal structures. Horizons showing a lamination on a scale from 0.5 to 5 cm are also quite common and often show a convex deformation of the laminae as a result from the drilling process (Figure 11a).

In addition, synsedimentary disturbances of the primary sediment fabric, such as bioturbation, become particularly apparent in these laminated layers. Erosional surfaces and therefore gaps in the sediment record also occur quite frequently, as indicated by laminae crosscutting one another (Figure 10a). For instance and as shown in Figure 11b, laminae onlapping a very distinct abrasion surface were found. Such a texture is very indicative for a hardground, likely representing a very long time of non-deposition.

Synsedimentary disturbances in the primary fabric also include horizons with strongly bended laminae that were interpreted as slumps (Figure 11c). As their formation requires a pronounced relief along the lake floor, the emergence of this facies is likely the result of tectonic processes associated with the evolution of the anticline structure.

A deposition in form of turbiditic currents is indicated by erosional surfaces overlain by fining upward sequences (Figure 10b). Although, the small thickness of 0.3-1.5 cm of the individual Bouma sequences paired with small grain sizes even at the base suggest a very distal origin, we reckon that these facies type could still comprise significant hiatuses.

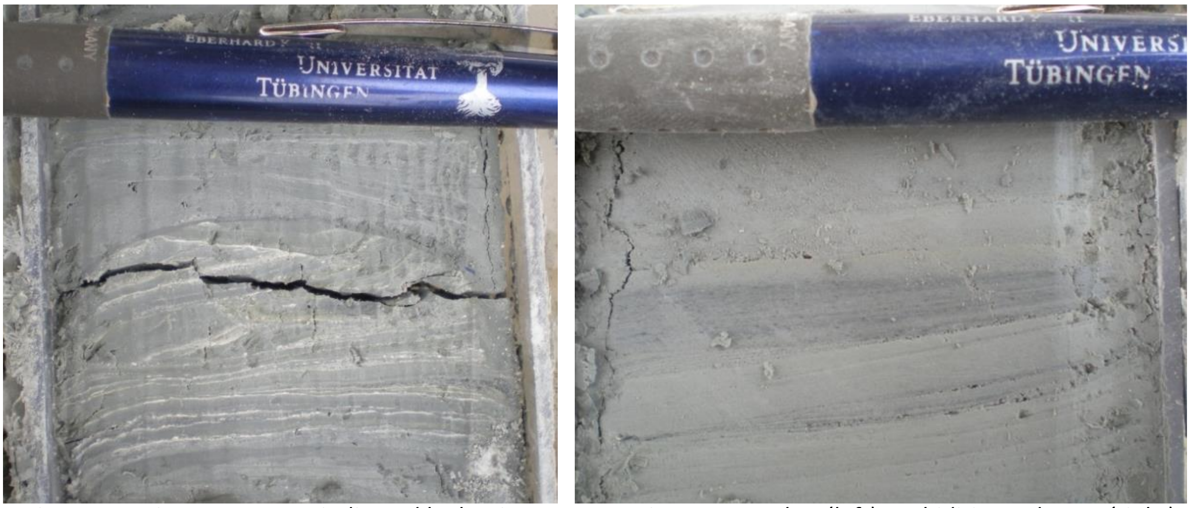


Fig. 10: Erosive contacts as indicated by laminae crosscutting one another (left), turbiditic mudstone (right).

Fig. 11: Convex deformation features (left), hardground with onlapping laminae (middle), slump facies (right).

Recapitulatory, it can be said that the sediment fabric in the Dafengshan anticline is deformed, disturbed or discontinuous in quite a few instances. The convex deformation features (Figure 11a), albeit, are likely owed to an inferior drilling technique compared to SG-1/SG-1B and can hence be disregarded. The other features, however, provide strong evidence for a tectonically induced synsedimentary deformation that could jeopardize the integrity of a continuous sediment record.

Throughout most parts of SG-1B, the sediment exhibits a relative uniform appearance, which is rarely disturbed and only episodically interrupted by laminated horizons and / or occurrences of carbonate congretions and thin gypsum layers. Concerning the sediment structure, the most distinctive difference to the Dafengshan core is the complete absence of drilling induced convex deformation features. Moreover, less signs for a synsedimentary deformation were found and the amount of dislocation generally seems to be far smaller compared to deformation features, which were revealed in the Dafengshan core. Therefore and unlike as in the Dafengshan anticline, the integrity of a continuous and largely undisturbed sediment record is ensured.

Geophysical logging data and cuttings from the exploration wells “Jian 1” and “Feng 2” imply that the lithology in the yet to be intersected horizons is principially the same as in the depth intervals covered by SG-1B and SG-2, respectively. In case of the Dafengshan anticline, cuttings mostly reveal interbedded shallow lake mudstone and basin platform marl (Figure 12). The Jianshan anticline is dominated by mud- and siltstones (Figure 13). The projected lithology is hence in every aspect promising.

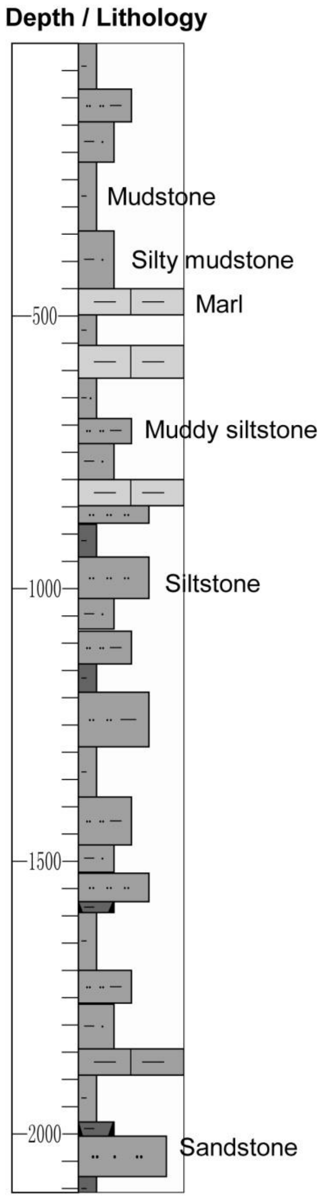


Fig. 12: Litholog, resistivity log and gamma ray log from exploration well “Feng 2”. The well is located in the Dafengshan anticline in very close proximity to the test core SG-2.

Fig. 13: Litho-log of exploration well “Jian 1”, which is located directly next to SG-1B.

In-depth palynological investigations with high resolution are only available for a short segment of core SG-1 so far. These results are highly promising and clearly provide a detailed reflection of the paleoclimate at the time. An interdisciplinary approach within TiP further revealed a good correlation in between pollen and magnetic proxies in this specific interval (Herb *et al*., in review).

In case of the Jianshan- and Dafengshan test cores, pollen samples were taken in larger intervals of several meters. The focus was thereby rather on assessing the general adequacy of the pollen record as archive for paleoclimate processes and not to unravel the processes itself.

In all of the investigated 50 sediment samples, which were taken in equidistant intervals along the two test cores, significant amounts of pollen and spores were found. Among them were at least 26 types of arboral pollen, 15 types of non-arboral pollen, 3 unidentified types, 4 types of wetland plants and 4 types belonging to ferns. The particular ratios as well as absolute pollen influx and concentration vary in between samples and can be found in the pollen diagrams in the appendix. Indicators of long-distance pollen as well as extraneous pollen are hardly given.

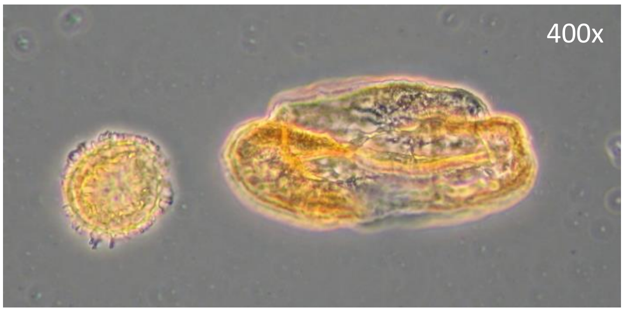


Fig. 14a: Allochthonous conifere pollen from the Jianshan anticline (SG-1B - 643 m depth).

Fig. 14b: Pinus Diploxylon-Habitus Scope (SG-1B - 723 m depth).

Presumably, as a result of deposit corrosion, pollen grains in some samples further show different grades of preservation, indicative for a mixture of pollen grains with an allochthonous vs. autochthonous origin (Figure 14). Strong effects of reworking processes are not indicated and it is believed that the processes mainly occurred on a very small scale and did not include a reworking and reallocation of significantly older material.

Considering all aspects from pollen influx to concentration and preservation, etc., both test cores likewise suggest good conditions of the analyzed samples. The prospects of a successful high resolution climate reconstruction by means of palynology are hence good. Minor shortcomings due to local reworking processes can however not be excluded. Differences in between the core SG-1B and SG-2B are mostly marginal and likely related to the different stratigraphic horizons and less to the cores' condition in general.

Sediment samples taken from the surface section in the Dafengshan anticline yield a very low abundance of pollen and spores. In addition, the quality of pollen preservation is far worse compared to samples retrieved from either of the drilling cores. As the lithology is dominated by lime- and in particularly mudstones just like in the cores, it is likely that the differences in concentration and quality of pollen grains are not a primary feature, but the result of dissolution due to alteration processes of meteoric water and weathering. From a palynological viewpoint, surface sections should hence be avoided, since in this case it is questionable if the pollen record is adequate to be used as a reliable climate proxy.

Dating based on magnetostratigraphy (TiP/pilot study) was found to work very well in case of SG-1 and SG-1B, providing a reliable age framework for further proxy data (Figure 15). The core SG-1B (including deepening) covers the age interval between 1.6-7.5 Ma; SG-1 is located more towards the basin center, where the sediment thicknesses are higher, covering the age interval between 0.1-1.5 Ma. For a more in-depth insight into the measurement procedure, rockmagnetic properties and broader tectonic implications, it is referred to Zhang *et al*. (2012, in review).

For the Jianshan anticline, a systematical decline in the sediment accumulation rates towards larger depths, as indicated by very low values in the bottom interval of the initial drilling campaign to 550 m, could not be verified (Figure 16). On the contrary, the SAR within the test core segment (550-723 m), which was drilled and investigated as part of this pilot study in particular to tackle this question, was found to be above-average. Altogether, three episodes with very high SARs (>7.32-6.03 Ma, 5.24-4.18 Ma and 3.60-2.58 Ma) are indicated. They are likely linked to reinforced erosion in the catchment area as a result of a regional tectonic uplift (Zhang *et al.,* in review). The mean SAR over the entire sequence amounts to 13 cm/ka, suggesting that the targeted age of 15 Ma can be reached at a depth of roughly 2 km. As seismic cross-sections imply a decreasing sediment accumulation rate at some point, this extrapolation should yet be considered as maximum estimate.

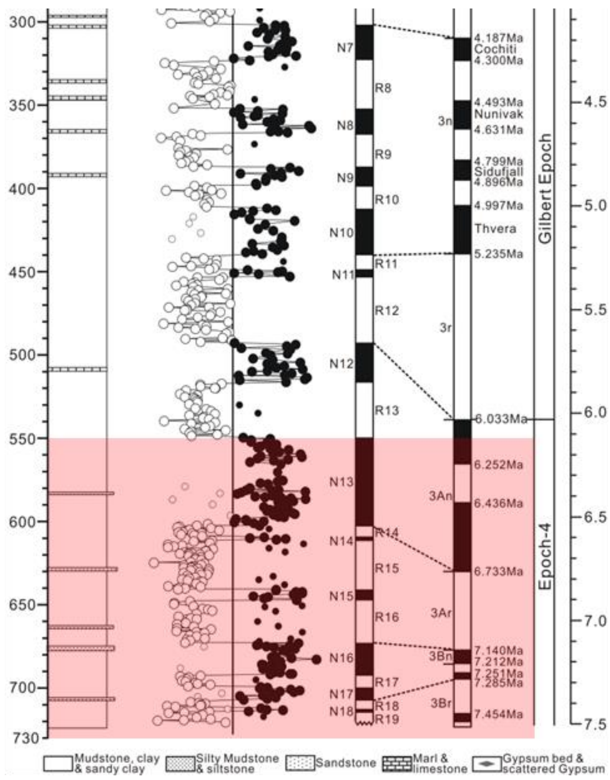


Fig. 15: Excerpt of magnetostratigraphic sequence from SG-1B. The test core segment is indicated in red. Modified after Zhang et al. (in review).

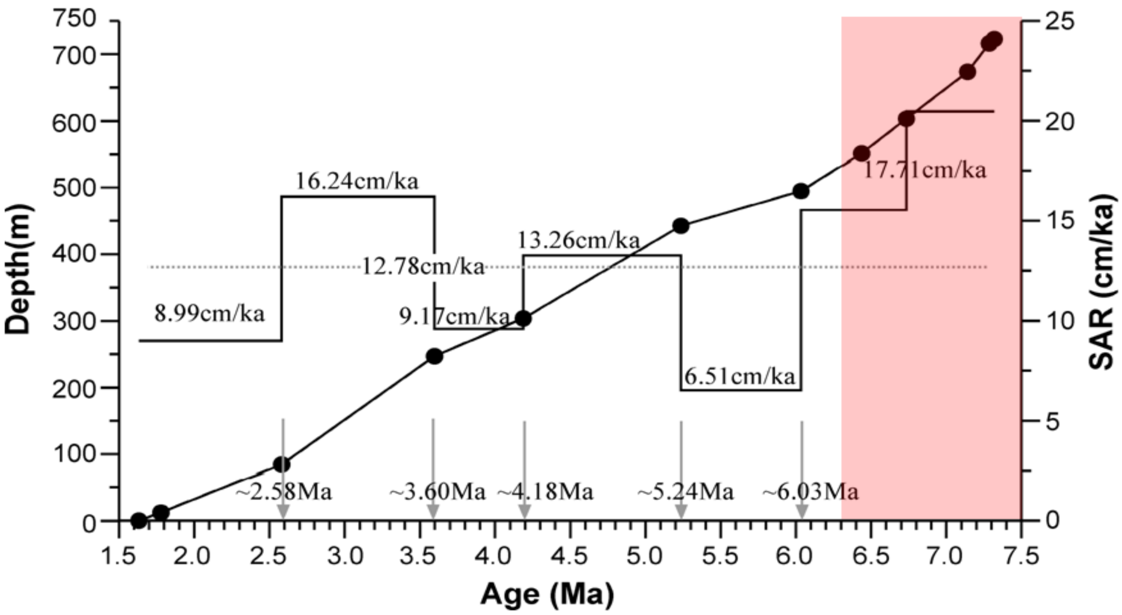


Fig. 16: Depth-age plot for core SG-1B. SARs are calculated from sediment thicknesses between the boundaries of correlated major chrons (test core segment marked in red). Modified after Zhang et al (in review).

In case of the Dafengshan test core (SG-2), a sequence of three normal and four reversed polarity intervals could be confidently defined (Figure 17), suggesting that magnetostratigraphy principally works. However, the sequence, even if combined with a nearby outcrop profile, is too short to be correlated with the GPTS without other constraints.

Further, it was found that compared to the magnetostratigraphic results of SG-1 and SG-1B, slightly more samples show outlying remanence directions that do not follow the main trend. Interestingly, these samples most often derive from horizons in which the sediment fabric was found to be disturbed in one way or another (Figure 17).

A negative influence on the magneto-stratigraphic quality due to tectonically induced syn- and post sedimentary deformation features must hence be considered as likely.

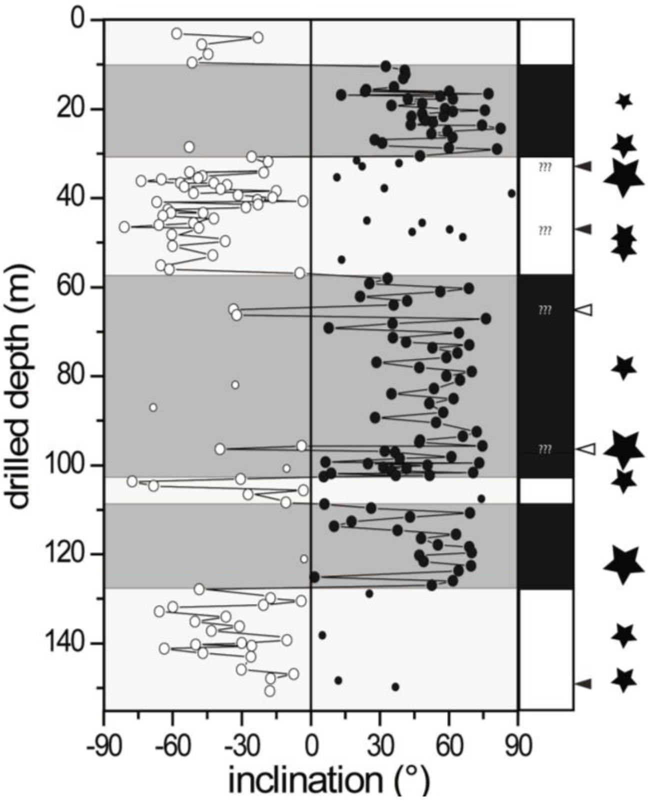


Fig. 17: Magnetostratigraphic sequence of the Dafengshan test core (SG-2). Horizons showing a disturbed sedimentary fabric are indicated by stars in the very right column. Larger symbol sizes represent progressively disturbed horizons.

Magnetic measurements of samples from the surface section in the Dafengshan anticline likewise reveal what seems like a reasonable sequence of normal and reversed polarity intervals (appendix). There are, however, some gaps in the stratigraphic profile due to buried horizons, which could not be sampled; also signs for a partial remagnetization of the sequence are indicated. In this way, it becomes clear that the overall quality is inferior compared to analogous approaches on drilling cores. Hence, also from a magnetostratigraphic viewpoint, surface sections should be considered only if no other alternatives are available.

As anticline structures represent potential target areas in the hydrocarbon exploration, we were in the very fortunate position to have access to a fine-meshed net of seismic lines, which were carried out, processed and to some degree also interpreted by PetroChina. The most revealing profiles run in NE-SW direction, providing cross-sections perpendicular to the fold axes of the Dafengshan- and Jianshan anticlines (Figure 18 & 19).

In both instances, the existence of a whole set of fault zones, along which the lithological units are displaced, could be clearly revealed. Growth strata onlapping the flanks of the anticlines are also indicated and characteristic for synsedimentary tectonics. The evolution of the anticlines should hence be understood as an ongoing process, in which older fault zones are episodically reactivated.

Further, it is indicated that in both Jianshan- and Dafengshan anticline, the SARs gradually decrease in pregrowth strata units.

The more diffuse reflection patterns that can be observed in some cross-sections of the Dafengshan anticline (e.g. Figure 19) could be interpreted in a way that the rocks were subjected to a stronger tectonic deformation, which in process might have led to the partial destruction of the primary sedimentary fabric. Nevertheless, also different processing techniques should be considered as potential cause for the differences in the quality of reflection patterns.

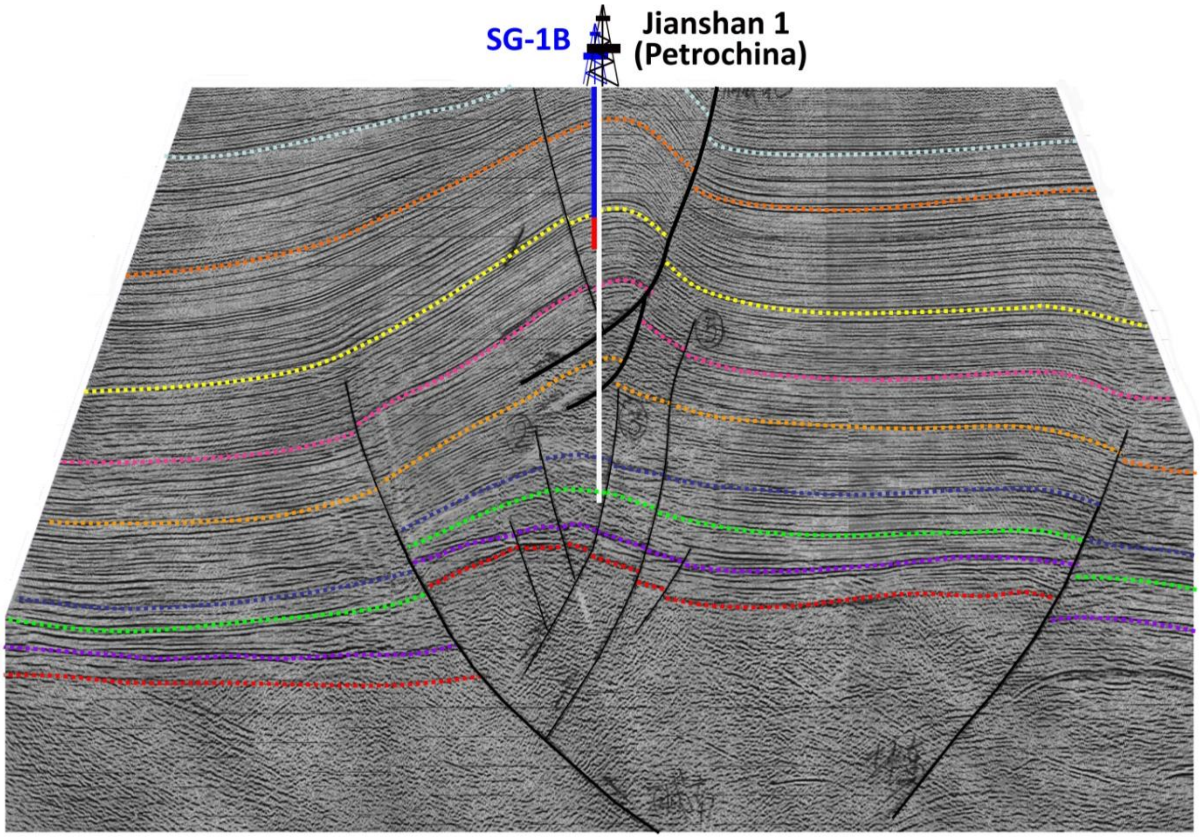


Fig. 18: Seismic cross-section over the Jianshan anticline. SG-1B and its deepening are indicated in blue and red colors, respectively. The exploration well "Jian1" is indicated in white. Fault zones are marked in black.

One shortcoming is that neither of the profiles from the Jianshan- and Dafengshan anticlines do overlap nor do they cover the area of the Chahansilatu sub-depression, where SG-1 is located. Therefore, a basin wide correlation of specific stratigraphic horizons solely based on the continuation of distinctive seismic reflectors is not possible. Nevertheless, on the basis of additional information from analogue studies on outcrops, a seismostratigraphic section connecting the different profiles could be established (appendix): It suggests that the top of the Shang Youshashan formation (8.1-15.3 Ma), which roughly marks the bottom end of SG-1B, is exposed in the center of the Dafengshan anticline (Figure 19).

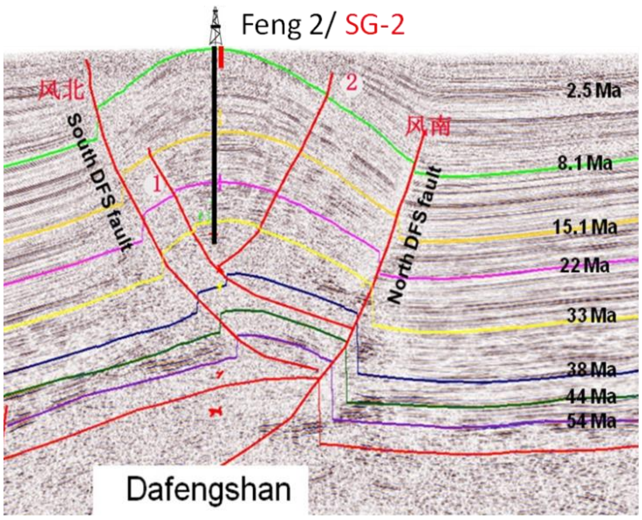
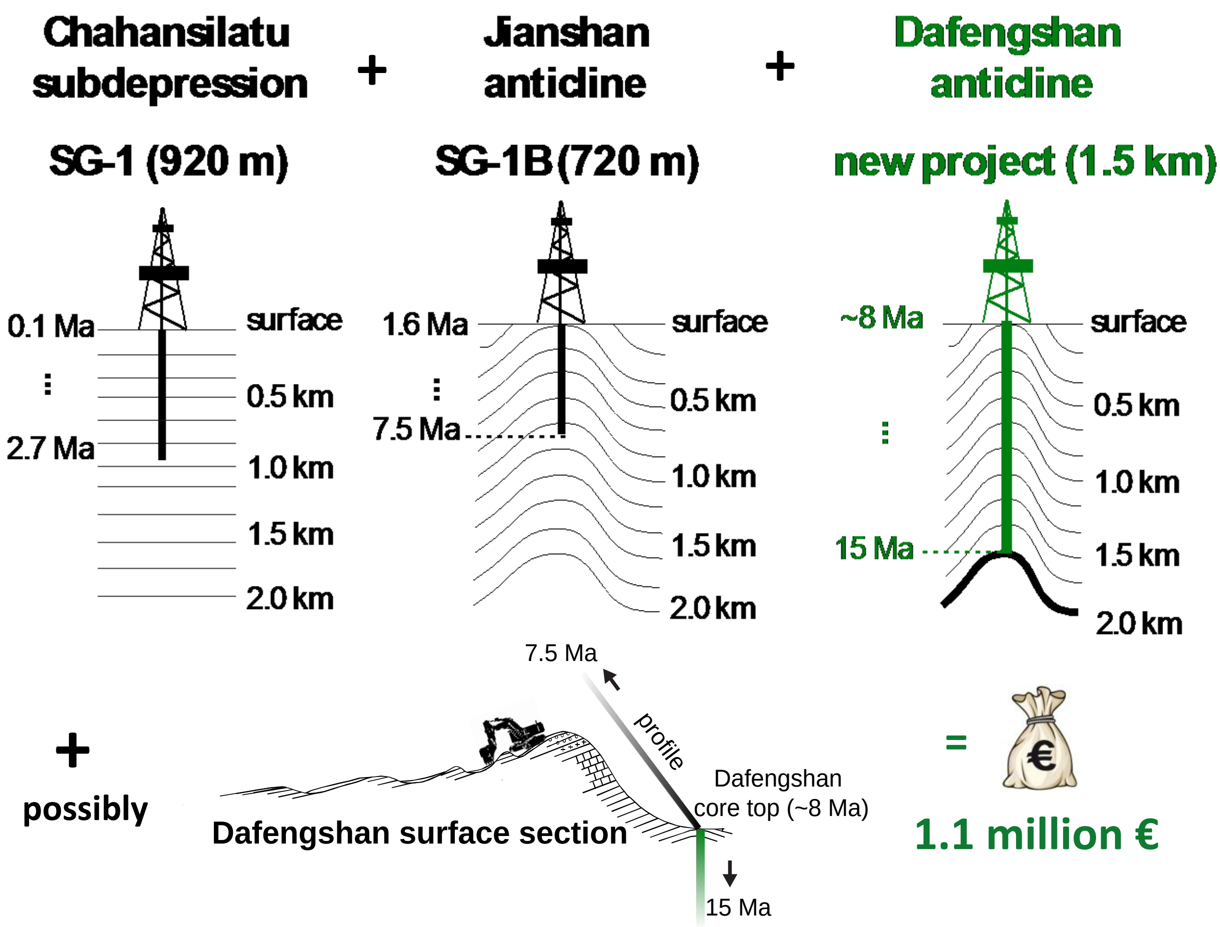


Fig. 19: Seismic cross-section over the Dafengshan anticline. The exploration well "Feng2" is indicated in black. Fault zones and SG-2 are indicated in red color.

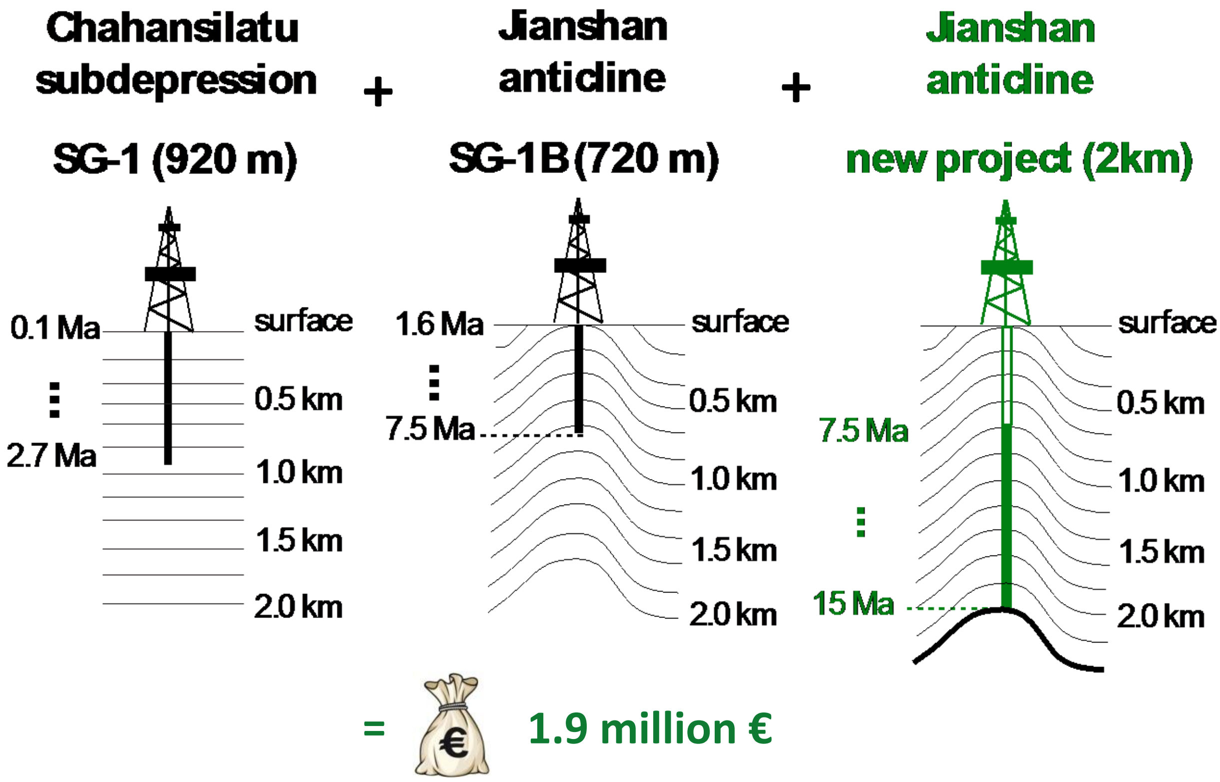
3. ALTERNATIVE SCENARIOS

Based on the findings that were presented in the previous chapter, the initial scenarios of how to acquire a continuous sequence from sub-recent to 15 million years could be greatly refined. Three alternative scenarios are henceforth outlined and schematically illustrated, including estimates of the respective costs.

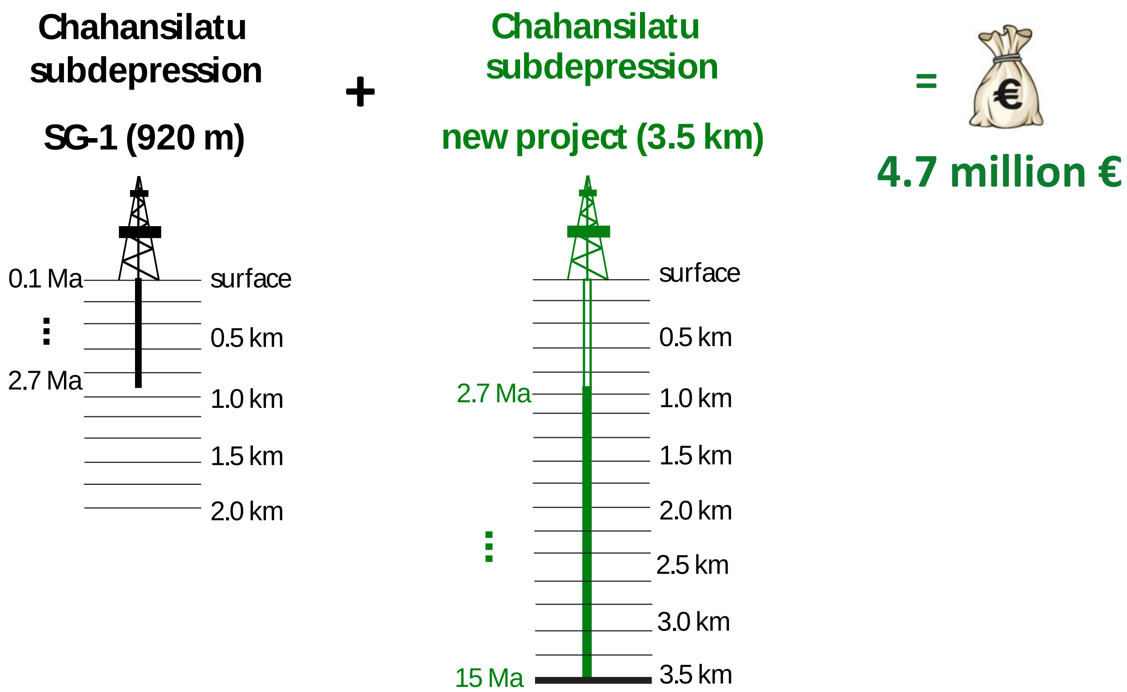
<u>Option 1</u>: Drilling to a depth of about 1200-1500 m into the center of the Dafengshan anticline and appending the results from SG-1 and SG-1B in order to cover the younger parts (<8.0 Ma) of the sedimentary sequence. This alternative represents the by far least expensive option (€ 1.1 millions), but there are several uncertainties / potential shortcomings involved with it: These include a rather high chance of disturbances or hiatuses in the sedimentary sequence due to tectonics and a rather unprecise age framework. The possibility of an age gap between the top of the Dafengshan anticline and the bottom end of SG-1B can hence not be ruled out and it might be necessary to resort on inferior results from the Dafengshan surface section.



<u>Option 2:</u> Drilling into the Jianshan anticline to a depth of roughly 2000 m. Since sediments of the most recent 1.6 million years are not exposed in the Jianshan anticline, an incorporation and correlation with results from SG-1 is further required. This alternative offers a good compromise between "option 1" and "option 3", yielding a low risk of shortcomings due tectonically induced deformation features paired with a yet reasonably low target depth. The costs for this scenario amount to € 1.9 millions and could be further reduced if the uppermost 720 m from the Jianshan anticline, which are already available from SG-1B, are intersected without extracting sediment cores.



Option 3: Drilling to a depth of at least 3000 m into the horizontal layers within the Chahansilatu sub-depression. This alternative is insofar appealing, as it does not require a combination and correlation of cores from different localities. Further, complications associated to fault zones or deformation processes in general are not being expected in a tectonically stable area like this. On the downside, the large target depth causes a substantial raise in costs with the estimated prices for drilling to 3000 and 3500m amounting to € 3.7 and € 4.7 millions. In order to reduce expenses, the uppermost 940 m, which were already sampled during the drilling of SG-1, could be intersected without taking cores.



4. CONCLUSION ON ALTERNATIVE PERSPECTIVES

The central finding of this assessment report is that the overall success chances for the proposed deep drilling project in the Qaidam basin are very good. A qualitatively high proxy inventory could be revealed in all test drilling cores, affirming the very positive results from SG-1 and SG-1B. The lithology of all investigated cores was found to be consistently fine grained and therefore ideally suited for a high-resolution, multiparameter analysis of the paleoclimate. Geophysical borehole data and cuttings from exploratory drillings (PetroChina) in the Jianshan- and Dafengshan anticlines further approve that the lithology does not significantly change in the depth interval, which is to be intersected in order to reach 15 Ma.

Paleo- and rockmagnetic investigations on test cores and along the surface section were further affirmative that dating based on magnetostratigraphy principially works. In case of the Jianshan anticline, the test core revealed that to a depth of 723 m, no systematical decrease in the sediment accumulation rate is indicated. The sequence in the Dafengshan anticline was too short to be confidently correlated with the GPTS and age estimates had to be derived from seismo-stratigraphic correlations with the Jianshan anticline instead. They are less confidable and not so precise.

Based on seismic cross-sections and the interpretation of sediment structures, it further became clear that in case of the very pronounced Dafengshan anticline, following points might be critical: (i) Potential hiatuses or repetitions in the sedimentary sequence due to small-scaled fault zones. (ii) The destruction of the primary sedimentary fabric due to synsedimentary tectonics.

	Chahansilatu sub-depression	**Jianshan anticline**	**Dafengshan anticline core / surface section**	
Quality of proxy inventory	✓	✓	✓	🚫
Lithological suitability	✓	✓	✓	✓
Logging data / cuttings available	–	✓	✓	–
Quality of magnetostratigraphy	✓	✓	✓	✓
Age dating / SAR available	✓	✓	–	–
No indications for deformation	✓	✓	🚫	–
Estimated depth to reach 15 Ma	3.5 km	≈ 2.0 km	≤ 1.5 km	
Prospects of success	very good	very good	uncertain	
Total costs	4.700.000 €	2.400.000 €	1.500.000 €	
Recommendation	✓	✓	🚫	

Table 1: Overview of benefits and shortcomings for the potential target areas.

In addition, the results from the surface section in the Dafengshan anticline do not look very promising in terms of pollen preservation and magnetostratigraphic approaches are likely biased as a result of alteration processes near the surface.

Due to these findings and after weighting the potential implications of a disturbed sediment fabric against the saving potential of a reduced drilling depth (<1.5 km), we came to the conclusion to disregard the Dafengshan anticline as potential target area for a future drilling campaign.

Drilling into tectonically less disturbed areas such as the Jianshan anticline and Chahansilatu sub-depression on the other hand can be highly recommended, since in both cases, the prospects of success to retrieve a continuous sequence are considered as very good. The reliable chrono-stratigraphic framework that is available for these locations from TiP combined with knowledge about the general basin geometry further allows a rather precise projection of the required drilling depth:

The target depth estimated to reach the intended 15 million year mark was found to be roughly 2000 m in the Jianshan anticline and 3000-3500m in the Chahansilatu sub-depression. The related costs would amount to € 1.9 million and € 3.7-4.7 million, respectively. The anticipated duration of the drilling campaign of course depends on the target depth and whether or not unforeseen problems arise, but lies in the range between one and two years.

5. APPLICABILITY AND OUTLOOK

This pilot study provides essential groundwork for a drilling project to 15 Ma in the Qaidam basin. Different strategies of how this goal can be achieved were outlined and evaluated in terms of costs, benefits and risks. The chances of unexpected problems, emerging in the envisaged larger drilling campaign could in this way be minimized in the forefront.

Further, with information derived from seismics and in particular from the test cores, the reachable goals are much clearer now and the required target depths for the potential drilling sites could be pinpointed with a far higher accuracy. Concrete expense budgets for different depth scenarios were also obtained, providing the necessary information to plan and advance the further funding process in the framework of the BMBF program “WTF Central Asia” and its counterparts on the Chinese side.

Alternatively, this pilot study could also mark an important milestone in the further development of a planned ICDP project proposal to intersect the entire sedimentary sequence in the western Qaidam Basin back to at least 50 million years. As a continuous record of such a length is exceptional for terrestrial archives even on a global scale, the results from this long-term project could give groundbreaking insights into the regional climate evolution in Central Asia and its driving forces.

As little piece in the big picture of coordinated research in the Tibetan Plateau region within TiP and CAME, this pilot study contributes to the scientific basis, on which political and administrative decision makers can develop environmental management strategies. In particular, questions related to the recent global climate change can thereby be addressed.

6. REFERENCES

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Zhang, W.L., Appel E., Fang X.M., Song C.H., Setzer F., Herb C., Yan M.D., in review: Magnetostratigraphy of drill-core SG-1b in the western Qaidam Basin (NE Tibetan Plateau) and tectonic implications". Geophysical Journal International.

7. PUBLICATIONS AND PRESENTATIONS

The following publication directly emanated from work that was conducted and / or financed in the framework of this pilot project:

- *Zhang, W., Appel, E., Fang, X.M., Song, C.H., Setzer, F., Herb, C., Yan, M. "Magnetostratigraphy of drill-core SG-1b in the western Qaidam Basin (NE Tibetan Plateau) and tectonic implications". Geophysical Journal International - in review (moderate revision).*

The results were also presented oral to the science community:

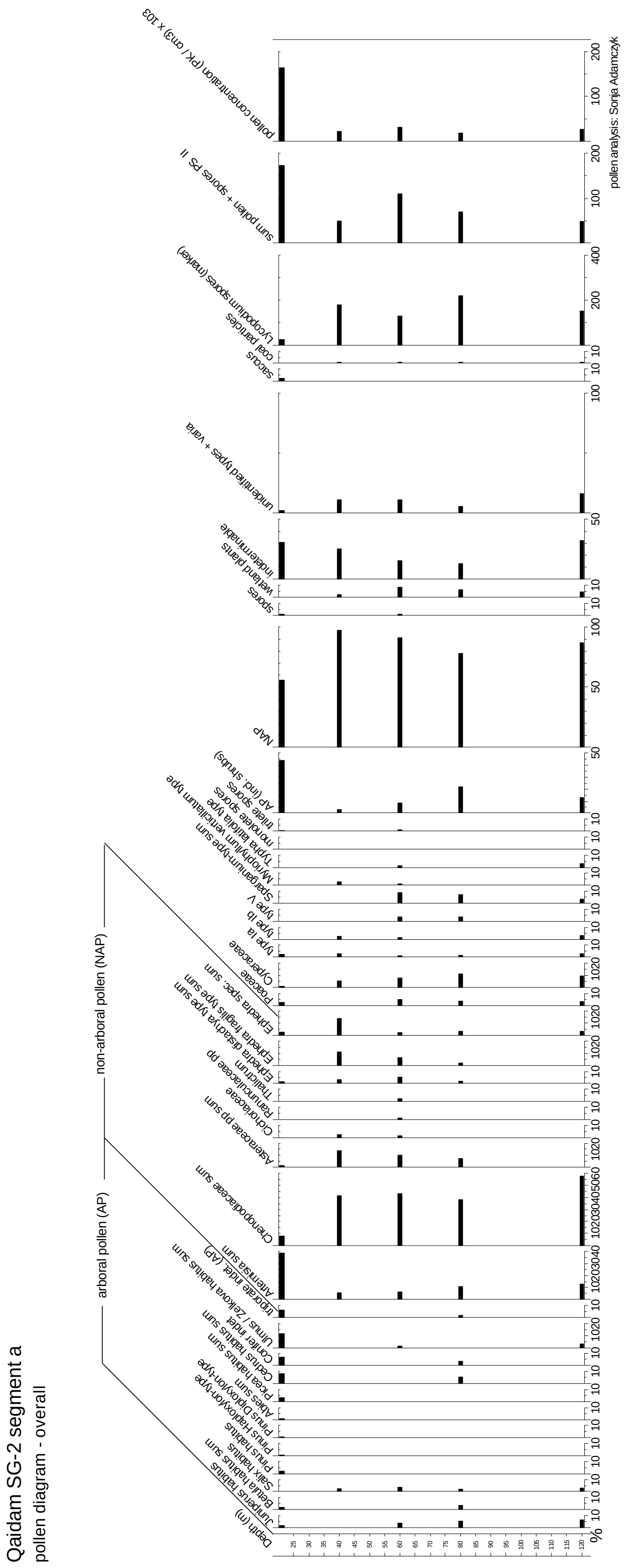
- *Setzer, F., Appel, E., Zhang W., Adamczyk S., Baumhoer M., Fang X.M., Pross J. and Mosbrugger V. "The climate archive Qaidam - Towards a future drilling project in Qaidam basin back to 15 Ma". Poster: 8th Sino-German Workshop on Tibetan Plateau research in Chengdu 2012, China.*

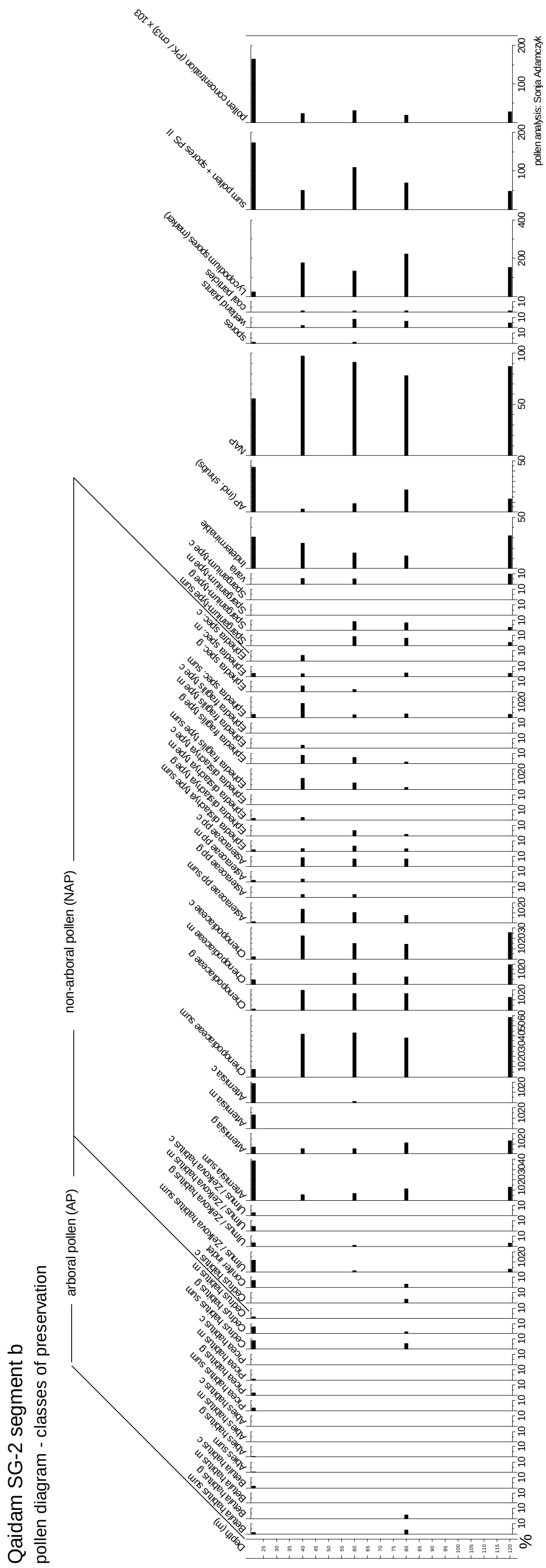
In addition, it is expected that future publications will be based on the work or incorporate findings that were made in this pilot study. This could for instance be the case for pollen analyses and the interpretation of sediment structures from the Jianshan- and Dafengshan test cores. At this stage, however, it is not yet clear in which way and in which journal(s) these results will be presented.

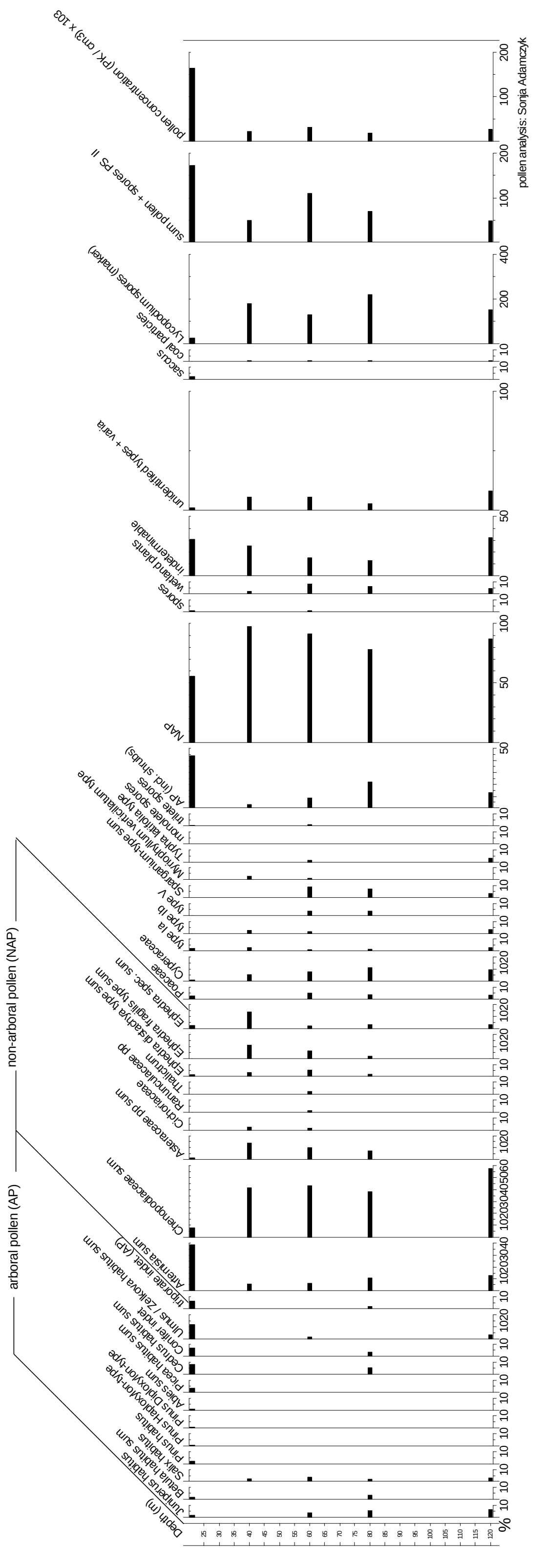
8. APPENDIX

8.1 Estimated costs

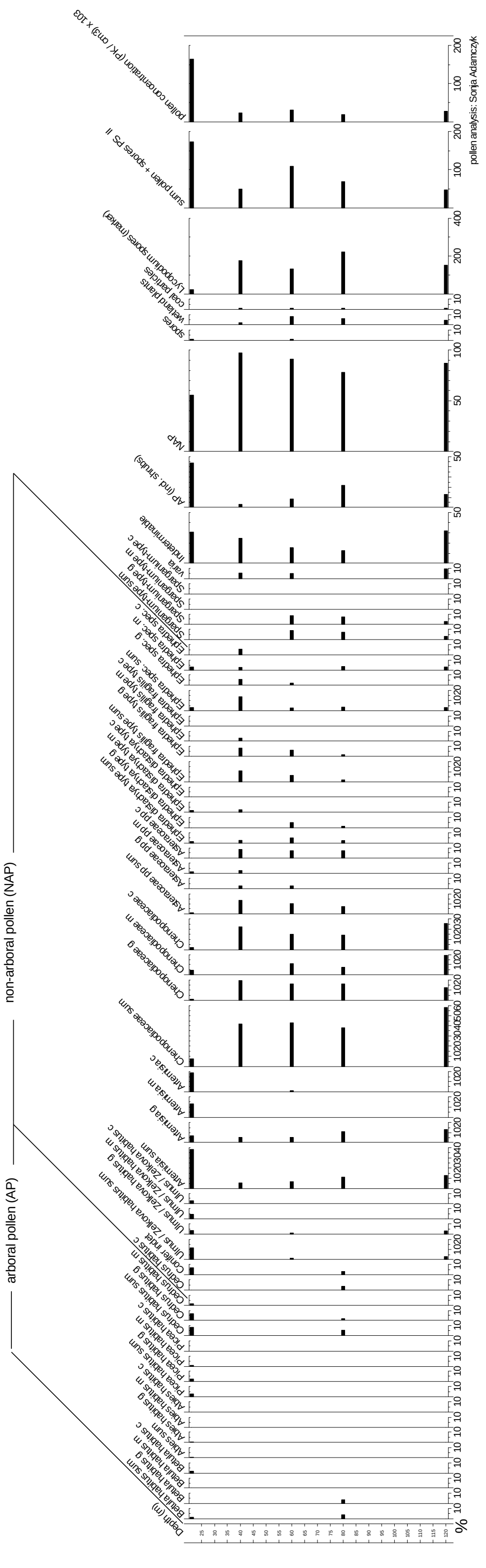
8.2 Pollen diagrams



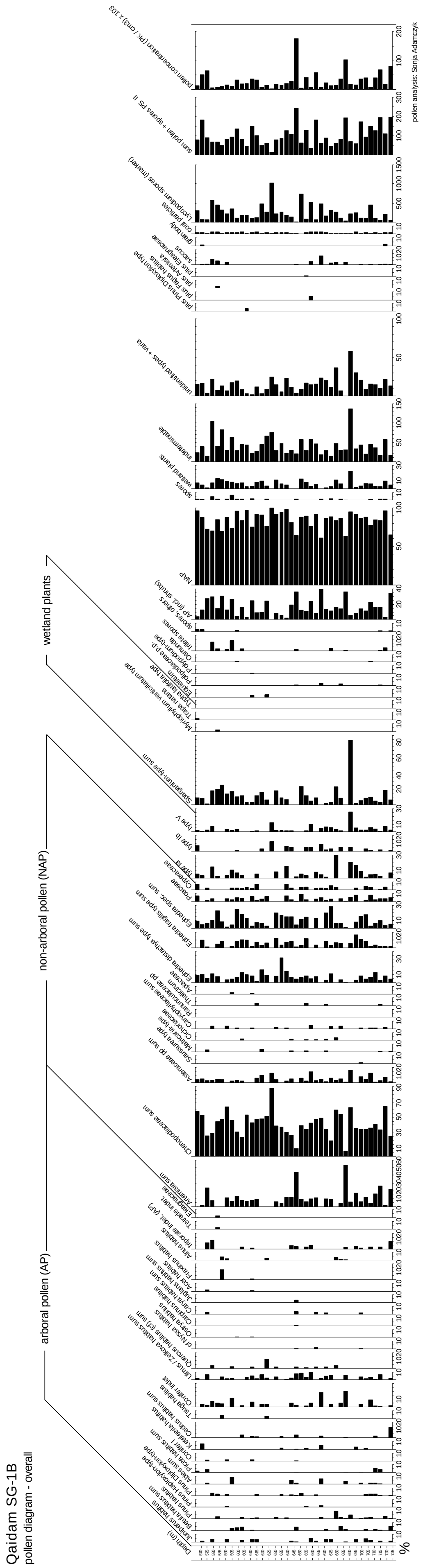


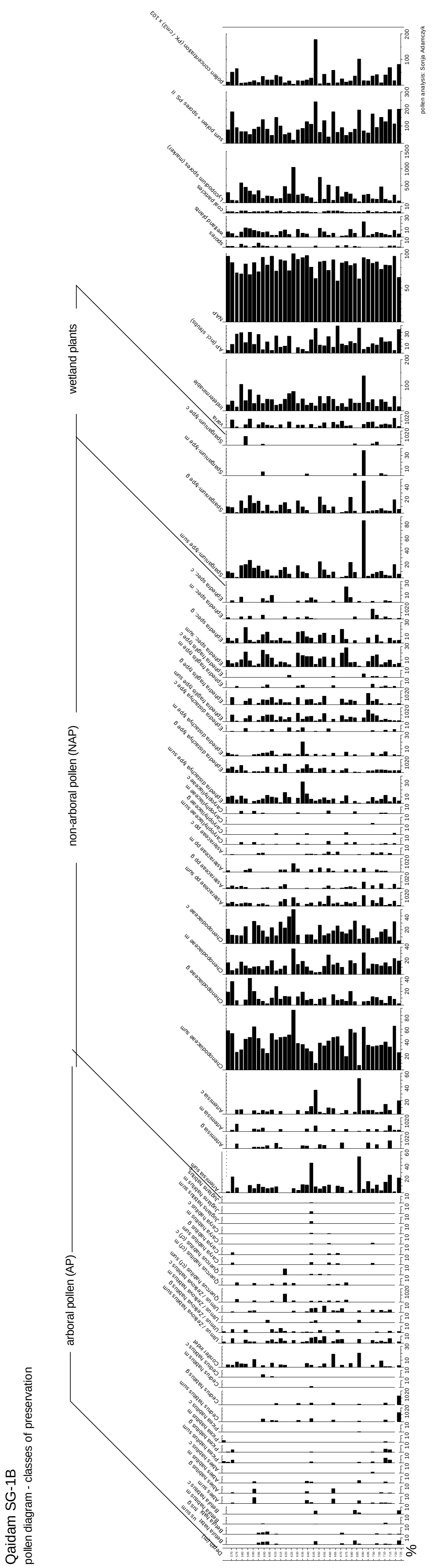


Qaidam SG-2 segment a
pollen diagram - overall



Qaidam SG-2 segment b
pollen diagram - classes of preservation


Qaidam SG-1B
pollen diagram - overall
arboral pollen (AP)
non-arboral pollen (NAP)
wetland plants
pollen analysis: Sonja Adamczyk
%


Qaidam SG-1B
pollen diagram - classes of preservation
arboral pollen (AP)
non-arboral pollen (NAP)
wetland plants
pollen analysis: Sonja Adamczyk
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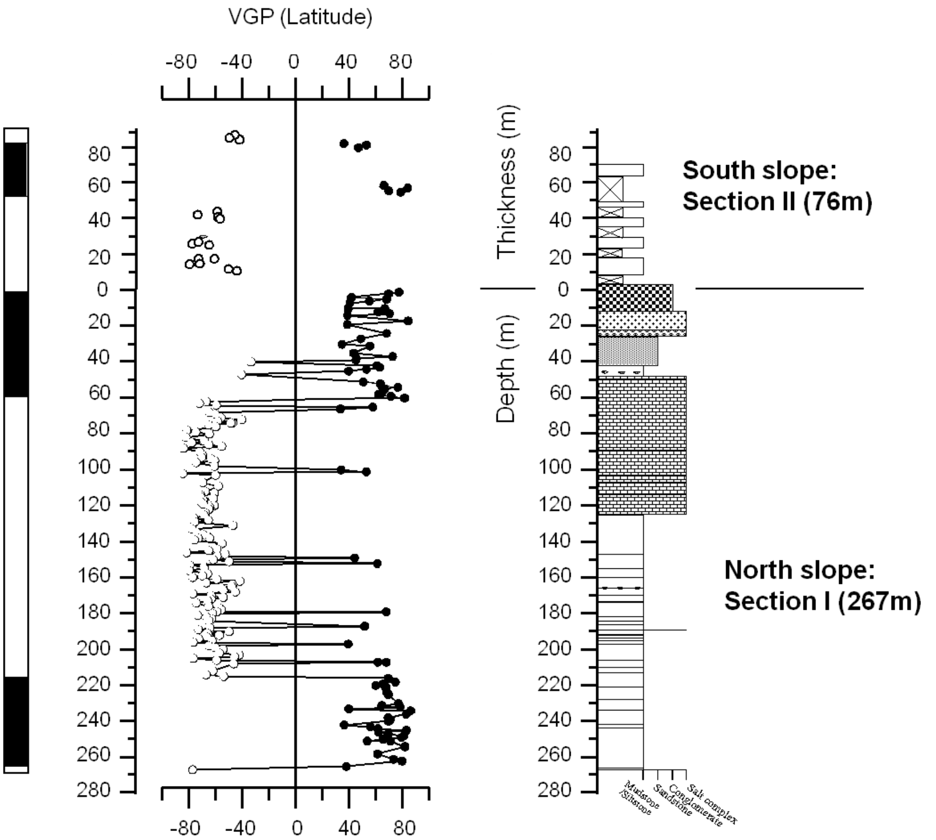
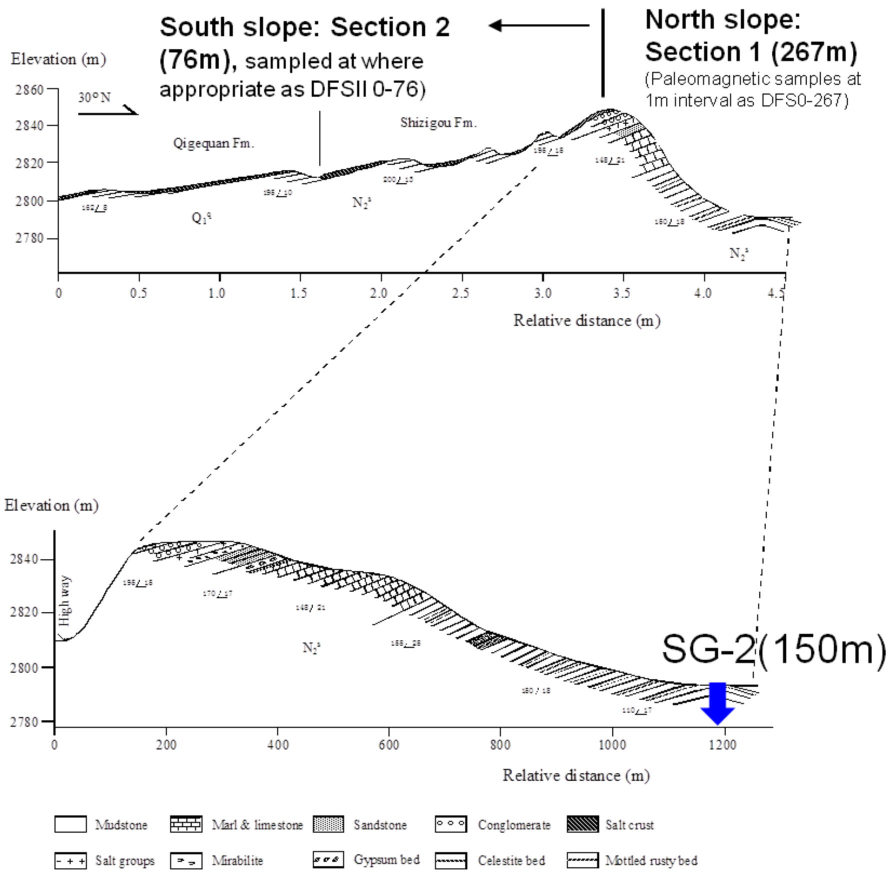
8.3 Dafengshan anticline - surface section (magnetostratigraphy /lithostratigraphic section)





8.4 Connected seismostratigraphic sections