Stress state measured at ~7 km depth in the Tarim Basin, NW China

Dongsheng Sun1,2, Hiroki Sone2, Weiren Lin3,4, Junwen Cui1, Bizhu He5, Haitao Lv6 & Zicheng Cao6

The in-situ stress state in the Tarim Basin, Northwest China, down to 7 km depth is constrained using the anelastic strain recovery (ASR) method and wellbore failure analysis. Results are consistent between the two methods, and indicate that the maximum principal stresses (σ1) are close to vertical and the intermediate and minimum principal stresses (σ2 and σ3) are approximately horizontal. The states of stress at the studied wellbore is in the normal faulting stress regime within the Tarim Basin rather than in the compressional tectonic stress regime as in the periphery of the Tarim Basin, which explains the presence of the normal faults interpreted in 3-D seismic profiles collected from adjacent areas. Our results demonstrate that the ASR method can be used for rocks recovered from depths as deep as 7 km to recover reliable stress state information. The in-situ stress measurement results revealed in this paper will help future development of the petroleum resources and kinematics study in the Tarim Basin.

The Tarim Basin is one of the largest Mesozoic-Cenozoic hydrocarbon-bearing Basins in Central Asia located in Northwest China between the Tianshan and Kunlun Mountains. The Tarim block has experienced a complex tectonic history during its formation and evolution process1. Himalayan collisional orogeny was the massive neo-tectonic movement which controlled the strong regional compressional tectonic regime of the Tarim block during the Late Cenozoic era2. Thus, the present-day in-situ stress state of Tarim Basin is also expected to be dominated by the Himalayan orogeny, promoting thrust faulting. Accordingly, the peripheries of the Tarim Basin are seismically active zones exhibiting pronounced intraplate deformation (Fig. 1a). However, the interiors of Tarim Basin records limited seismic activity and show relatively minor deformation3. While the compressional thrust structures at the periphery generally become the focus of investigation, a large number of small normal faults associated with the Paleozoic-Cenozoic extensional structures are also interpreted from seismic data which have triggered discussion on why such structures exist and what marks the transition in the stress state4,5 (Fig. 1b).

We studied wellbore data and core samples recovered from the SN-X ultra-deep vertical well (deviation < 2 degrees) located at the Shunnan area (Fig. 1a), one of the key focus areas in the Tarim Basin6–8 for potential oil and gas production. The Ordovician Yingshan Formation, buried at 6000–7000 m depth, is the key reservoir of the Shunnan oil-field, which consists of intraclastic shoal limestone with tiny vugs and karst holes. The cores were recovered from the SN-X well from about 6200–7100 m depth within the Lower Ordovician Yingshan formation (O2y) and the Lower Ordovician Penglaiiba formation (O1p) (Fig. 1c). The formation temperature at the coring interval was 170–190 °C. Five cores were retrieved from different depths in the SN-X well for ASR measurements. These samples mostly consist of calcite with a minor amount of dolomite. Descriptions of each sample are given in Table 1.

Measuring and constraining in-situ stress becomes more difficult as depth increases. Generally, hydraulic fracturing (HF) is the best known and most direct method for in-situ stress magnitude estimation in the subsurface9,10. However, the applicability of the HF method may be limited at great depths due to the temperature and pressure limits of the packer material. Observation of wellbore failures by borehole imaging is an indirect strategy to infer subsurface stress magnitudes which can complement HF stress measurements. But wellbore failures are not always prevalent in image logs and only impose limits on the range of possible stress magnitudes. Up to date, the maximum depth at which hydraulic fracturing was successfully employed for in-situ stress measurements is

1Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, 100081, China. 2Department of Civil and Environmental Engineering, Geological Engineering Program, University of Wisconsin-Madison, Madison, WI, 53706, USA. 3Graduate School of Engineering, Kyoto University, Kyoto, 615-8540, Japan. 4Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, Nankoku, 783-8502, Japan. 5Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China. 6Tarim Oil-field Company, PetroChina, Korla, Xinjiang, 841000, China. Correspondence and requests for materials should be addressed to D.S. (email: dongshengsun@cags.ac.cn)
9 km, and the maximum depth of stress profiles constrained by borehole breakouts and drilling-induced tensile fractures (DITFs) is 8 km.11

Anelastic strain recovery (ASR)12,13, on the other hand, is a core-based method which relies on the measurement of the time-dependent strain recovery of rocks due to the sudden release of in-situ stress. There are strict requirements about sample isotropy and assumptions on certain rock behavior, but there is a relatively explicit theoretical basis and measurements can be conducted relatively easily as long as oriented core samples are available. Merits of the ASR method are that it is technically simple and can recover the full three-dimensional in-situ stress tensor14–16. The restriction for the application of ASR method is obviously that it requires measurable amounts of recovery strain. This translates to depth limits of application since it takes longer for deeper core samples to reach the surface and strain recovery rates of rocks decrease with time. Therefore measurements of anelastic recovery strain should be conducted as soon as possible after the cores have been released from the borehole.

### Table 1. Basic properties and depths of the core samples.

| Core Num. | Formation         | Classification    | Top depth (m) | Bottom depth (m) | Natural density (g/cm³) | Porosity (%) | Mineral composition (%) | Period (hour) | Azimuth (°) |
|-----------|-------------------|-------------------|---------------|------------------|------------------------|---------------|------------------------|---------------|-------------|
| ASR-1     | Yingshan formation | Micritic limestone | 6293.09       | 6293.29          | 2.652                  | 1.25a         | Calcite: 100            | 65            | 82          |
| ASR-2     | Yingshan formation | Micritic limestone | 6369.54       | 6369.71          | 2.646                  | 40           | Calcite: 60 Dolomite: 40| 40            | 125         |
| ASR-3     | Penglaiba formation| Dolomitic limestone| 6410.38       | 6410.56          | 2.649                  | 80           | Calcite: 70 Dolomite: 30| 80            | 91          |
| ASR-4     | Penglaiba formation| Dolomitic limestone| 6955.41       | 6955.64          | 2.657                  | 1.15a         | Calcite: 100            | 48            | 155         |
| ASR-5     | Penglaiba formation| Dolomitic limestone| 7022.28       | 7022.42          | 2.669                  |               |                        | 96            | 2           |

Figure 1. (a) Earthquake epicenters (red circles, scaled according to magnitude) from 1973 to 2003 around the Tarim Basin3, where the yellow circle is the SN-X well position, (b) Seismic profile along the transect A-A’ in panel (a) in the Lunnan Lower Uplift located in a Meso-Cenozoic normal fault zone, where the red lines represent the normal faults interpreted from 3D seismic data4, (c) A tectonic profile across the Tarim Basin from south to north along the transect B-B’ in panel (a)5, on which the location of the SN-X well is projected. Coring interval of SN-X is about 6200–7100 m in the Lower Ordovician Yingshan formation (O2y) and the Lower Ordovician Penglaiba formation (O1p). Depths of the ASR samples are also shown to the right.
in-situ stress. On the other hand, the magnitude of recovery strains of a core may increase with depth because of the larger magnitude of stress release (i.e. stress magnitudes are generally proportional to depth). Therefore, depth can also work to our advantage at times for ASR measurements and the depth limit of application of the ASR method is not necessarily determined solely by the time required for core recovery.

In this study, we first present the orientations and magnitudes of in-situ stresses at ~7 km depth estimated by the ASR method. Then information about the DITFs observed in borehole image logs, as well as some drilling engineering parameters, are used to constrain the possible range of in-situ stress magnitudes. The results of the ASR method and the wellbore failure information are generally consistent and allow us to evaluate the reliability of the methods. Our results reveal that the current stress state in the interior of the Tarim Basin is a normal faulting stress regime, in contrast to the compressional tectonic stress regime developed in the periphery of the Tarim Basin.

Results

The anelastic recovery strain. As mentioned above, a good-quality anelastic recovery strain curve is the key to obtain reliable in-situ stress information as well as the validity of the assumptions that the rock is homogeneous, isotropic and linear viscoelastic. The anelastic recovery strain results at ~7 km depth are shown in Fig. 2. Figure 2a shows an example of all raw measurements of the anelastic recovery strains for sample ASR-4 (6955.41–6955.64 m) along with the temperature recorded during the strain measurement. The temperature curve shows about a ± 1 °C fluctuation caused by the relatively large day/night temperature variation in the Tarim Basin. Accordingly, the recovery strain data is also showing fluctuations that has a negative correlation with the temperature fluctuation. This is consistent with the fact that the temperature coefficient of the strain gauges is −11 × 10⁻⁵/°C and the linear thermal expansion coefficient of ASR samples is about 7 × 10⁻⁵/°C [16,17], which would lead to a negative correlation between strain and temperature. Thus, results clearly show that the temperature effect did not mask the recovery strain data and the overall trend reflects true mechanical rock deformation in response to the stress release. Figure 2b shows the principal and mean anelastic strain components deduced from the independent strain measurements based on least squares regression. According to the principle of ASR method, ASR measurements should be started as soon as possible after the cores were recovered. However, the time spans are 40–96 hours for the SN-X ultra-deep hole in this study (Table 1). As shown in Fig. 2c, the measurement results of mean strains show that three sets of data are valid but not those from samples ASR-3 and ASR-5. Data from ASR-3 and ASR-5 were invalid probably because the time span of 80 and 96 hours from stress release to the start of measurement was too long to record large enough magnitudes of anelastic recovery strain.

Magnitude of the principal stresses. Using the same method as previous studies, we estimated the stress magnitudes from the ASR data as follows. We made the same two assumptions made by the relevant literatures that the vertical stress is equal to the density-related gravitational overburden stress [18–20] and that the ratio of the shear recovery compliance, \( J_{s(t)} \), and volumetric recovery compliance, \( J_{v(t)} \), is constant such that \( J_{s(t)}/J_{v(t)} = 1.5621 \). Under these assumptions, the magnitudes of the three principal stresses (the maximum, intermediate and minimum principal stresses \( \sigma_1, \sigma_2, \sigma_3 \), respectively) could be determined from the measured anelastic recovery strain values of the three core samples. Because the original pore pressure in the ASR core samples are unknown, the principal stress magnitudes were calculated as a range of possible values based on the upper and lower limit of the pore pressures. The upper bounds of the pore pressures were suggested to be 88.7, 90.4 and 125.2 MPa (corresponding to mud density 1.41, 1.42 and 1.80 g/cm³, respectively) for samples ASR1, ASR2 and ASR4, respectively, from the mud weight adapted during the drilling process to stabilize the well by the managed-drilling pressure technology [21] (Table 2). The lower bound of the pore pressure was considered to be the hydrostatic pressures which are 62.9, 63.7 and 69.6 MPa for the three depths of the ASR samples, respectively (Table 2). The results show that the uncertainty in the pore pressure did not have drastic influences on the principal stress magnitudes estimated from the ASR method and stress magnitudes predicted from both the upper and lower bound of the pore pressure stayed within the normal faulting stress regime for all 3 samples. The relationship between the three principal stresses and the vertical stress is consistent, being \( \sigma_1 > \sigma_3 > \sigma_2 > \sigma_3 \) for all the three samples suggesting a consistent stress regime in the studied depth interval (Table 2).

Figure 3a–c show the stress polygons used to constrain the magnitudes of the horizontal in-situ stresses at 6800 m depth using pore pressure values 68.0, 88.4 and 108.8 MPa, corresponding to the lower bound (hydrostatic pressure), middle (the average of lower and upper bounds), and upper bound (the mud pressure) values, respectively. Presence of the DITFs requires the stress state to be on the left side of the blue contours representing equilibrium between the minimum borehole circumferential stress, \( \sigma_{0b} \), and rock tensile strengths, \( T_p \). Several contours are drawn for tensile strengths corresponding to 0, −10 and −20 MPa. However, we see that the influence of \( T_p \) variation is not significant, therefore hereon carry out the discussion assuming \( T_p = 0 \) MPa. The absence of breakouts also requires the stress state to be below the red contours representing equilibrium between the maximum \( \sigma_{0b} \) and the rock UCS (unconfined compressive strength) = 79 MPa [21]. The magnitudes of \( \sigma_{\text{hmin}} \) [18] further constrained to be between 129–149 MPa from the instantaneous shut-in pressures (ISIPs) observed in hydraulic fracturing experiments conducted in a nearby well in the same area of the Tarim Basin [22], and the vertical stress \( \sigma_z \) is 176.8 MPa calculated from the density log. The stress states constrained based on the different pore pressure scenarios varied from a normal faulting stress regime in the upper limit pore pressure case (Fig. 3a), to a stress state around the boundary of normal and strike slip faulting stress regimes in the lower limit pore pressure case (Fig. 3b). Overall, the stress regimes fall within the normal or near normal faulting stress regime. The presence of an over-pressured gas reservoir at 7000 m depth gives us plausible reasons to believe that the pore pressure is not at the lower limit case but rather greater than that, thus the in-situ stress state is likely in the normal faulting regime.
Figure 3d shows the results of constrained $\sigma_{H_{\text{max}}}$ and $\sigma_{h_{\text{min}}}$ magnitudes normalized by $\sigma_v$ at different depths. The green, blue and red polygons indicate the range of normalized stress magnitudes for the upper, middle and lower bound pore pressure magnitudes, respectively. The $\sigma_v$-normalized results from the ASR method are also shown by the red filled circles which all lie in the normal faulting stress regime. The stress states suggested from both methods are in good agreement.

**Orientation of the principal stresses.** The orientations of the reference line on the cores (ASR Line of Fig. 4a) were successfully reoriented to the geographic reference frame by viscous remnant magnetization analysis using five to nine specimens from each ASR cores. Figure 2d shows the three-dimensional principal stress orientations determined based on the results of ASR measurements carried out on the cores from different depths. The results show that the orientations of the maximum principal stress, $\sigma_1$, are sub-vertical, plunging between 72°–80°, and the intermediate and minimum principal stresses are sub-horizontal (Table 2). DITFs were also observed in the borehole image log (Fig. 4b) at 6400–6900 m depth, within the depth range of ASR cores. The azimuths of the maximum horizontal stress inferred from these DITFs are about 67° East from North (Fig. 2d), which falls within the range indicated by the ASR method.
Discussion

The state of stress at ~7 km depth in the central Tarim Basin and its implication. This paper presents results from a rare ultra-deep stress measurements at ~7 km depth which is certainly the deepest measurement made within the Tarim Basin and the entire Qinghai-Tibet Plateau area. The results from both the ASR and DITF methods consistently show that the maximum principal stresses ($\sigma_1$) are close to vertical and the intermediate and minimum principal stresses ($\sigma_2$) and ($\sigma_3$) are approximately horizontal. The state of stress is thus in the normal faulting stress regime at ~7 km depth in the SN-X well.

The present-day state of stress around the Tarim Basin is dominated by a regional compressional tectonic stress field by the Himalayan collisional orogeny\textsuperscript{2, 29}. Therefore, it may seem that our results are in conflict with the regional tectonic background. However, extensional structures also formed within the Tarim Basin from Proterozoic to Cenozoic\textsuperscript{4, 5}, which have been suggested to be linked to a series of geological events such as the breakup of the Rodinia supercontinent, stress relaxation after the Kunlun Caledonian collisional orogeny, and the tectonic escape with a certain degree of rotation triggered by the far-field effect of the Himalayan collisional orogeny\textsuperscript{4, 5, 29}.

The large scale (~600 km) cross-section in Fig. 1c clearly shows that thrust faults close to the mountain ranges are cutting through young sediments (even Quaternary) suggesting recent thrust faulting environment. But at the center of the basin, the thrust faults only reach up to the Permian sediments. Moreover, a clear normal fault
sequence is developed at the center of the basin which mainly cuts through the Triassic formations and the bottom of the Jurassic formation, but not through the middle- and late-Jurassic and the Cretaceous sediments (Fig. 1b). These observations suggest that the central region of the basin was under normal faulting stress environment in early Jurassic and Triassic periods. Therefore, somehow between Permian and Jurassic period, the stress state at the center of the basin transitioned from a thrust to a normal faulting environment, whereas it remained thrust faulting at the perimeter of the basin. In this study, we provide direct evidence that the present-day stress state in the depression of the lower Ordovician stratum is in the normal faulting stress regime. This suggests that the stress environment in the central Tarim Basin may have remained extensional through the period from the middle Jurassic to today without any intensive tectonic activities and re-construction of the stress regime. The transparent seismic section, absent of any faulting structures, in the shallower Cretaceous and Paleogene sediments (Fig. 1b) also supports this interpretation. The in-situ stress state is one of the fundamental boundary conditions in any geomechanical and geodynamics analyses. The in-situ stress results revealed in this paper will be a basis for future studies of the extensional structures found in the Tarim Basin.

Applicability of the ASR method to ultra-deep hard rocks. Lin et al.16 has shown that the ASR method can be applied in hard rocks within the range of about 2400–4500 m depth. This study is the first successful application of the ASR method to ultra-deep hard rocks at 6293–6955 m depth, where anelastic strain measurements only started after 40–65 hours from the time the cores were released from the in-situ stress. The anelastic strain curves from the onsite measurements were of good except for the ASR-3 and ASR-5 samples. The good agreement of the results from the ASR and DITF methods shows that the ASR method is also applicable and effective for stress measurements at ultra-depth. The fact that in-situ temperature and stress/pressure magnitude does not impose any technical depth limit to the ASR method especially makes it a strong option for stress...
measurements at ultra-depth. From the micritic limestone and dolomitic limestone samples used in this study, effective information of anelastic recovery strain were recovered when strain measurements started less than 80 hours after the cores were released from the in-situ stress. However, for ASR-3 and ASR-5 samples whose strain measurements started after 80 and 96 hours from the stress release, this was not the case. The strain recovery in the ASR-3 stopped after an initial sharp increase, and the ASR-5 sample exhibited almost no strain recovery (Fig. 2c). This time threshold for ASR measurements should certainly vary according to various factors such as stress magnitudes. For instance, soft rocks typically have bigger anelastic recovery strain than hard rocks when subject to the same stress release16, 30, but whether the time threshold of the anelastic recovery deformation for soft rocks are longer or shorter than hard rocks should also depend on the viscoelastic time constant that governs the time scale of the strain recovery, which is not explored in detail yet.

Comparison between the ASR and DITF methods. Although the ASR and DITF methods generally yielded in-situ stresses that agree with each other, there were certain discrepancies between the two stress results. With regards to the orientation of the principal stresses, we observed symmetrical en-echelon inclined DITFs with consistent inclination throughout the observed depth interval, which suggests that the maximum principal stress ($\sigma_1$) is slightly but consistently deviated to the southeast direction from vertical. However, ASR results show that the azimuth of the maximum principal stress ($\sigma_1$) varies with depth and not necessarily consistent with the direction inferred from the inclined DITFs. Since DITFs form under the direct influence of the current in-situ stress, we believe that the deviation direction from the DITF is more reliable. The deviation direction was actually in the southeast direction but the ASR method was not able to capture this direction. With regards to the magnitude of the principal stresses, the ASR method estimates the full three-dimensional stress tensor and its magnitude based on the overburden stress and the ASR compliances and the ASR measurement method, usually combined with the assumption that the vertical stress is also one of the three principal stresses. Subsequently, Matsuki14 extended the technique to a three-dimensional method and showed that it could be used to estimate the full stress tensor with the assumption that the rock is homogenous, isotropic and linearly viscoelastic, and that the shear and volumetric compliances are independent. The orientations of the three principal in-situ stresses are consistent with the orientations of the three principal anelastic recovery strains for isotropic viscoelastic materials. Thus, the orientations of the principal stresses can be determined from the anelastic recovery strain data measured in at least six independent directions. Also, the magnitudes of the stress components can be recovered as a function of the anelastic recovery strains (mean and deviatoric strain components), material constants (shear and volumetric compliances, linear thermal expansion coefficient) and pore pressure16, 32. In this paper, we conducted ASR measurement based on the principle suggested by Matsuki14 and employed the same apparatus and procedures used by Lin et al.16, 30. As shown in Fig. 4a, the Z-axis was parallel to the borehole axis. Six cross-type wire strain gauges and six single-type gauges were mounted on the ASR sample surface to measure the anelastic recovery strain in nine directions, including six independent directions.

In order to verify the homogeneity and isotropy of the ASR samples, elastic velocities of the ASR samples were measured in a triaxial apparatus at in-situ stress magnitude conditions (Autolab-2000c, New England Research Inc.). Cylindrical specimens for these velocity tests were cored in three orthogonal directions with the axis of the specimens being either parallel to or perpendicular to the bedding of the larger ASR sample. The measurements were made at room temperature on cylindrical specimens of 2 inch length and 1 inch diameter. Figure 4b shows the measured compressional and shear wave velocities as a function of isotropic confining pressure. The results demonstrate that the elastic velocities in three orthogonal directions are fairly close to each other with differences less than 3% when the confining pressure was higher than 30 MPa. The results verify that the cores used for ASR in-situ stress measurements are nearly homogenous and isotropic. Slightly greater difference at low pressure is present though that could be caused by the presence of microcracks in some samples.

DITF method to constrain in-situ stress state. It is well known that stress concentrations are produced around the borehole after drilling which can be described by the Kirsch equations2 for cylindrical boreholes. Wellbore failures will occur if the perturbed stress field around the wellbore meets the failure criterion of the rock26, 34. Figure 4c shows high resolution electrical resistivity images of the borehole wall clearly indicating the presence of drilling-induced tensile fractures (DITFs). All DITFs were also found to be inclined with respect to the borehole axis forming an en-echelon pattern. These en-echelon tensile fractures are clearly drilling-induced (Fig. 4c) because natural fractures were not present in the cores and the tensile fractures clearly cut across the pre-existing planes of weakness35.

The statistics of the inclined DITFs indicate that the DITFs are symmetrically distributed around the borehole wall, and that the azimuths of the maximum horizontal stress inferred from DITFs are about 67° East from North. Thus the maximum horizontal stress azimuths are roughly consistent between the DITF and ASR methods (Fig. 5a). Nearly all the DITFs in the interval are inclined in a preferred direction with the inclination angles, $\omega$, ranging between 4–18° (Fig. 5b). The azimuthal span of the inclined DITFs ranges between 2–8° (Fig. 5c).

Methods

ASR method for estimating in-situ stress state. The ASR method was proposed by Voight31 based on the empirical observation that the anelastic strain recovered in a rock is proportional to the pre-existing stress state when the rock is homogenous and rheologically isotropic. Initially, it was proposed as a two-dimensional in-situ stress measurement method, usually combined with the assumption that the vertical stress is also one of the three principal stresses. Subsequently, Matsuki14 extended the technique to a three-dimensional method and showed that it could be used to estimate the full stress tensor with the assumption that the rock is homogenous, isotropic and linearly viscoelastic, and that the shear and volumetric compliances are independent. The orientations of the three principal in-situ stresses are consistent with the orientations of the three principal anelastic recovery strains for isotropic viscoelastic materials. Thus, the orientations of the principal stresses can be determined from the anelastic recovery strain data measured in at least six independent directions. Also, the magnitudes of the stress components can be recovered as a function of the anelastic recovery strains (mean and deviatoric strain components), material constants (shear and volumetric compliances, linear thermal expansion coefficient) and pore pressure16, 32. In this paper, we conducted ASR measurement based on the principle suggested by Matsuki14 and employed the same apparatus and procedures used by Lin et al.16, 30. As shown in Fig. 4a, the Z-axis was parallel to the borehole axis. Six cross-type wire strain gauges and six single-type gauges were mounted on the ASR sample surface to measure the anelastic recovery strain in nine directions, including six independent directions.

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Figure 5d shows the inlet mud density parameters from the drilling engineering data. As shown in Fig. 5e, the deviation of the borehole axis from vertical was smaller than two degrees, which is normally regarded to have indistinguishable effect on the inclination of DITFs. Therefore the inclination of DITF is due to the deviation of the principal stress axis from the vertical direction, not the borehole itself.

Magnitudes of principal stresses by the DITF method. Given the Kirsch equation below, we can estimate the magnitude of the far-field principal stresses if all other parameters are constrained.

$$\sigma_{\theta} = \sigma_{Hmax} + \sigma_{hmin} - 2(\sigma_{Hmax} - \sigma_{hmin})\cos2\theta - (P_m - P_p) - \alpha_T \Delta T \frac{E}{(1 - \nu)}$$

Equation (1)

In Equation (1), $\sigma_{Hmax}$ and $\sigma_{hmin}$ are the magnitudes of the (total) far-field maximum and minimum horizontal stresses. $\theta$ is the circumferential position relative to the azimuth of $\sigma_{Hmax}$, $\sigma_{m}$ is the effective circumferential stress, $P_m$ is the downhole mud pressure exerted on the wellbore wall by the drilling mud, $P_p$ is the pore pressure, $\alpha_T$ is the linear thermal expansion coefficient, $\Delta T$ is the difference between mud and formation temperatures, $E$ and $\nu$ are Young’s modulus and Poisson’s ratio, respectively. It is important to note that Equation (1) applies only when the borehole axis is aligned with one of the principal stresses. As was seen above, this is not the case in our study where the principal stress axis is slightly deviated from the vertical direction. However, if the misalignment between the borehole axis and a principal stress is small, one can still apply the Kirsch equations to constrain the magnitude of stress. For instance, Sone showed that the misalignment of the borehole axis and the principal stress up to 15 degrees had little effect on the stress magnitudes deduced from the wellbore failures. Thus, we assume that the same is true for this study and we apply Equation (1) to constrain the magnitude of the maximum horizontal stress. If $\sigma_{\theta}$ from Equation (1) becomes negative, the tensile stress pulls apart the borehole wall to form a vertical DITF, assuming the lower bound tensile strength of 0 MPa. As a representative example, we constrain stress state at 6800 m depth because it locates between the ASR samples and abundant high quality DITFs were observed at that depth (see Fig. 5a).

The basic parameters required to constrain the maximum horizontal stress magnitude at 6800 m depth are listed in Table 3. The vertical stress ($\sigma_v$) was calculated from the density log. The minimum horizontal stress was estimated from the instantaneous shut-in pressures (ISIP) observed during a hydraulic fracturing conducted in...
a nearby well. The downhole mud pressure was taken as the sum of the maximum mud pressure and 95% of the excess pumping pressure at the surface used to circulate the mud. The mud outlet temperature and the formation temperature were obtained by onsite logging. The coefficient of linear thermal expansion of limestone was $7 \times 10^{-6} \text{K}^{-1}$, which was measured by strain gauges using equipment similar to the equipment used for ASR measurements. The Young's modulus $E$ and Poisson's ratio $\nu$ are derived from P and S wave elastic velocities measured in three orthogonal directions. The UCS came from past measurements from the same formation. As pressure difference between $P_w$ and $P_d$ exist, the contribution of radial stress $\sigma_r = P_w - P_d$ to the rock compressional strength should not be ignored, and the internal friction coefficient of limestone was taken as 0.59.

Unfortunately, the formation pore pressure has not been measured in SN-X well and we can only infer ranges of possible pore pressure values from other information. The drilling engineering data showed that the mud density used for drilling was 1.45 g/cm$^3$ when the bit passed 6800 m depth on Sep 5, 2014. The drilling operation in this interval continued down to 6890 m depth by Sep 15, 2014 with a mud density of 1.60 g/cm$^3$. Then downhole logging including FMI imaging was conducted on Sep 16, 2014. Thus, the images revealing the DITFs were obtained ~11 days after the drilling reached 6800 m. During this 11 day time period, the pore pressure around the borehole would have increased towards equilibrium with the mud pressure, and may have been anywhere between the hydrostatic pore pressure of 68 MPa and the upper limit of 108.8 MPa constrained by the mud weight. Therefore we constrained the stress magnitudes based on the lower (hydrostatic), middle and upper (mud weight) bounds of the pore pressure (Fig. 3a–c).

In this study, the outlet mud temperature and the undisturbed temperature of the formation at 6800 m depth were about 58°C and 178°C, respectively. However, no measurements exist for the downhole temperature of the circulating mud which is necessary to constrain the $\Delta T$ in Equation (1), and thus necessary to evaluate the magnitude of the thermal stress. The downhole temperature of the circulating mud is a difficult parameter to constrain, as there are many factors influencing the mud temperature including the geothermal gradient, borehole diameter, circulation time, mud flow rate, specific heat and thermal conductivity of the surrounding rock, cemented casing depth, and etc. Brudy et al. estimated the temperature difference between the undisturbed formation temperature and the circulating mud temperature during drilling to be about 80°C at 6800 m depth in the KTB main borehole whose geothermal gradient is 27.4°C/Km. In the SN-X well, the drilling mud at surface temperature was pumped into the borehole and the geothermal gradient was ~27°C/Km, which is almost the same with the geothermal parameters of the KTB main borehole. Thus we used the same value as Brudy et al., a temperature difference of 80°C at 6800 m depth, as the maximum amount of cooling the rock experienced. The resulting thermally-induced tensile stress is about 45 MPa. Calculations show that changes in this temperature difference value by, for instance, ±20°C has a small impact (less than 4 MPa) on the estimated magnitude of $\sigma_{inh}$ Thus, error in our estimate of the thermal stress has a minor impact on the estimated magnitude of $\sigma_{inh}$ and does not change the conclusions of this study.

References
1. Tang, L. An approach to major tectogenesis of Tarim Basin. Experimental Petroleum Geology 19(2), 108–114 (1997). (in Chinese with English abstract).
2. Sobel, E. R. & Dumitru, T. A. Thrusting and exhumation around the margins of the western Tarim Basin during the India-Asia collision. J. Geophys. Res. 102, 1043–1063 (1997).
3. Carroll, A. R., Graham, S. A. & Smith, M. E. Walled sedimentary Basins of China. Basin Research 22, 17–32 (2010).
4. Liu, Y. et al. Analysis on the faults of Awati-Manjiaer lower ridge, central Tarim Basin, NW China. Chinese Journal Geology 49(3), 947–964 (2014) (in Chinese with English abstract).
5. Li, Y. et al. Meso-Cenozoic extensional structures in the Northern Tarim Basin, NW China. Int. J. Earth. Sci. 102, 1029–1043 (2013).
6. Liu, L. et al. Paleo-Cenozoic reservoir beds and their favorableness in Tazhong Areas of Tarim Basin, Northwest China. Journal of Petroleum Science and Engineering 68, 1–18 (2009). (in Chinese with English abstract).
7. Yun, L. & Cao, Z. Hydrocarbon enrichment pattern and exploration potential of the Orcovician in Shunan area, Tarim Basin. Oil and Gas Geology 35(6), 788–797 (2014). (in Chinese with English abstract).
8. He, B. et al. Late Ordovician paleo-seismic records of the Manjiaer depression and adjacent areas in Tarim Basin, Xinjiang, and its geologic significance. ACTA Geolica Sinica 35(6), 1805–1817 (2010). (in Chinese with English abstract).
9. Haimson, B. C. & Fairhurst, C. Initiation and extension of hydraulic fracture in rocks. Society of Petroleum Engineers Journal 310–318 (1967).
10. Haimson, B. C. The hydraulic fracturing method of stress measurement: theory and practice. Comprehensive Rock Engineering 3, 395–412. Pergamon Press: Oxford, 1993.
11. Brudy, M., Zoback, M. D., Fuchs, K., Rummel, F. & Baumgartner, J. Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength. J. Geophys. Res. 102(88), 18453–18475 (1997).
12. Blanton, T. L. The relation between recovery deformation and in situ stress magnitudes. SPE/DOE Symposium on Low Permeability Gas Reservoirs. Denver, Colorado. 11624 (1983).
13. Warpiniski, N. R. & Teufel, L. W. A viscoelastic constitutive model for determining in situ stress magnitudes from anelastic strain recovery of core. SPE 61st Annual Technical Conference and Exhibition. 15368 (1986).
14. Matsuki, K. Three-dimensional in-situ stress measurement with anelastic strain recovery of a rock core. 7th International Congress on Rock Mechanics. Aachen, Deutschland. 1, 557–560 (1991).
15. Byrne, T. B. et al. Anelastic strain recovery reveals extension across SW Japan. Geophys. Res. Lett. 36, L23310 (2009).
16. Lin, W. et al. Determination of three dimensional in-situ stresses by anelastic strain recovery measurement of cores at great depth. Tectonophysics 426, 221–238 (2006).
17. Micro-Measurement, Tech Note TN-513-1. Measurement of thermal expansion coefficient using strain gauges 119–129 (2010).
18. Lin, W. et al. Preliminary results of stress measurement by using drill cores of TCDP Hole-A: an application of anelastic strain recovery method to three dimensional in-situ stress determination. Terr. Atmos. Ocean. Sci. 18, 379–393 (2007).
19. Cui J. et al. Determination of three-dimensional in-situ stresses by anelastic strain recovery in Wenchuan Earthquake Fault Scientific Drilling Project Hole-1 (WFSD-1). Tectonophysics 619–620, 123–132 (2014).
20. Sun, D. et al. Three-dimensional in-situ stress determination by anelastic strain recovery and its application at the Wenchuan Earthquake Fault Scientific Drilling Hole-1 (WFSD-1). Science China: Earth Sciences 57(6), 1212–1220 (2014).
21. Matsuki, K. Anelastic strain recovery compliance of rocks and its application to in situ stress measurement. Int. J. Rock Mech. Min. Sci. 45, 952–965 (2008).
22. Yuan, J. The drilling mud technique of SN501 wellbore. Chemical Enterprise Management 116–117 (2015). (in Chinese with English abstract).
23. Ding, W. L., Fan, T. L., Huang, X. B. & Li, C. Y. Upper Ordovician paleo tectonic stress field simulating and fracture distribution forecasting in Tazhong area of Tarim Basin, China. Geological Bulletin of China 30(4), 588–694 (2011). (in Chinese with English abstract).
24. Li, Y., Guo, J. & Zhao, J. The hydraulic fracturing simulation key technology and solution of low permeability reservoir at ultra-depth. Drilling & Production technology 30(2), 56–58 (2007). (in Chinese with English abstract).
25. Tamaki, M., Suzuki, K. & Fujii, T. Paleocurrent analysis of Pleistocene turbidite sediments in the forearc Basin inferred from anisotropy of magnetic susceptibility and paleomagnetic data at the gas hydrate production test site in the eastern Nankai Trough. Mar. Pet. Geol 66, 404–417 (2015).
26. Peska, P. & Zoback, M. D. Compressive and tensile failure of inclined well bores and determination of in situ stress and rock strength. J Geophys. Res 100(B7), 12791–12811 (1995).
27. Brudy, M. & Zoback, M. D. Drilling-induced tensile wall-fractures: implication for determination of in-situ stress orientation and magnitude. Int. J. Rock Mech. Min. Sci 36, 191–215 (1999).
28. Sone, H. Mechanical properties of shale gas reservoir rocks and its relation to the in-situ stress variation observed in shale gas reservoirs [Dissertation], Stanford University (2012).
29. Beck, R. A. et al. Stratigraphic evidence for an early collision between northwest India and Asia. Nature 373, 55–58 (1995).
30. Nagano, Y., Lin, W. & Yamamoto, K. In-situ stress analysis using the anelastic strain recovery (ASR) method at the first offshore gas production test site in the eastern Nankai Trough, Japan. Mar. Pet. Geol. 66, 418–424 (2015).
31. Voight, B. Determination of the virgin state of stress in the vicinity of a borehole from measurements of a partial anelastic strain tensor in drill cores. Felsmechanik und Ingenieurgeologie 6, 201–215 (1968).
32. Matsuki, K. & Takeuchi, K. Three-dimensional in-situ stress determination by anelastic strain recovery of a rock core. Int. Rock Mech. Min. Sci. Geomech. Abstr. 30, 1019–1022 (1993).
33. Kirsch, G. Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. Zeitschrift des Verlins Deutscher Ingenieure 42, 707 (1898).
34. Sone, H. & Zoback, M. D. Viscous relaxation model for predicting least principal stress magnitudes in sedimentary rocks. J. Petroleum Sci. and Eng. 124, 416–431 (2014).
35. Zoback, M. D. Reservoir Geomechanics (Cambridge University Press, 2007).
36. Sun, D. Experimental study of anelastic strain recovery in-situ stress measurement methods and its application [Dissertation], Chinese Academy of Geological Sciences (2014).
37. Yin, S. et al. In situ stress field evaluation of deep marine tight sandstone oil reservoir: A case study of Silurian strata in northern Tazhong area, Tarim Basin, NW China. Marine and Petroleum Geology 80, 49–69 (2017).
38. Laderian, A. Prediction of temperature profile in oil wells. International Journal of Engineering 13, 77–89 (2000).

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Author Contributions
D.S., J.C., B.H., H.L and Z.C. were responsible for collecting and processing the data. D.S. and H.S. conducted the DITF processing. D.S., J.C., B.H., H.L and Z.C. were responsible for interpretation and writing.

Additional Information
Competing Interests: The authors declare that they have no competing interests.

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