The nature and origins of decametre-scale porosity in Ordovician carbonate rocks, Halahatang oilfield, Tarim Basin, China

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Abstract: At >7 km depths in the Tarim Basin, hydrocarbon reservoirs in Ordovician rocks of the Yijianfang Formation contain large cavities (c. 10 m or more), vugs, fractures and porous fault rocks. Although some Yijianfang Formation outcrops contain shallow (formed near surface) palaeokarst features, cores from the Halahatang oilfield lack penetrative palaeokarst evidence. Outcrop palaeokarst cavities and opening-mode fractures are mostly mineral filled but some show evidence of secondary dissolution and fault rocks are locally highly (c. 30%) porous. Cores contain textural evidence of repeated formation of dissolution cavities and subsequent filling by cement. Calcite isotopic analyses indicate depths between c. 220 and 2000 m. Correlation of core and image logs shows abundant cement-filled vugs associated with decametre-scale fractured zones with open cavities that host hydrocarbons. A Sm–Nd isochron age of 400 ± 37 Ma for fracture-filling fluorite indicates that cavities in core formed and were partially cemented prior to the Carboniferous, predating Permian oil emplacement. Repeated creation and filling of vugs, timing constraints and the association of vugs with large cavities suggest dissolution related to fractures and faults. In the current high-strain-rate regime, corroborated by velocity gradient tensor analysis of global positioning system (GPS) data, rapid horizontal extension could promote connection of porous and/or solution-enlarged fault rock, fractures and cavities.

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Hydrocarbon reservoirs in carbonate rocks in which pores and fractures have been enlarged by dissolution are common in many petroliferous basins in the world (Loucks 1999; Ahr 2011; Garland et al. 2012). These reservoirs typically have low to moderate recovery efficiencies (Wordlaw and Cassan 1978) owing to heterogeneity and anisotropy in the size, spatial arrangement, and connectivity of open pores and fractures. The behaviour of such reservoirs is notoriously challenging to characterize and predict. In some instances, a palaeokarst model is a useful paradigm for predicting open pores and fractures. In modern karst settings, corrosive surficial conditions and groundwater flows form various subsurface and geomorphological (landscape) features, including caves (e.g. Ford and Williams 1989). Some of these features collapse and coalesce during subsequent burial (Loehmann 1988; Mazzullo & Harris 1991; James and Choquette 2012). Such palaeokarst features are typically marked by evidence of near-surface conditions at the time of formation, including cave-fill sediments and distributions that match palaeotopography. Palaeokarst porosity is reduced by cavity-fill sediments, compaction (stylolites) and mineralization. Mineral fills might not be diagnostic of porosity formation at shallow depths, as cements may accumulate during subsequent burial or hydrothermal fluid flow. Such reservoirs are widely recognized in China (e.g. Tian et al. 2016).

However, deep-seated dissolution and cavity formation (e.g. Giles and de Boer 1990; Vahrenkamp et al. 2004) as well as structural processes create pore space in carbonate rocks, and cavities and cavity-filling minerals may both be deep burial phenomena. Dissolution along fractures, for example, is widely reported (Nelson 1985; Narr et al. 2006). If deep-seated (mesogenetic; Choquette and Pray 1970) dissolution is important in a given reservoir, predictions based on shallow (epigenetic) dissolution and palaeokarst processes may be misleading. The possibility of large-scale (volumetrically significant) dissolution at great depth (>1 km) has been doubted (e.g. Ehrenberg 2006; Ehrenberg et al. 2012). But workers agree that discerning cavities formed by shallow (epigenetic) from those owing to deep-seated (mesogenetic) dissolution is challenging, as by definition the cavities themselves preserve scant evidence of their origin.

In this study, we use observations from outcrops and core to show that fracture-related, deep dissolution and porous fault rock are widespread in Yijianfang Formation rocks. Evidence from the Keping Uplift outcrops, 100 km SW from producing Yijianfang Formation carbonate rocks in the Halahatang oilfield show that multiple stages of fracture-related dissolution are common in exposed Middle Ordovician rocks. Stable isotopic analyses indicate cavity-filling cements precipitated from fluids at depths of c. 220–2000 m. Crosscutting relations and abutting show that some fractures and vugs formed and became cement filled prior to later dissolution events and formation of subsequent generations of fractures and vugs. Together these relations show that dissolution (probably multiple instances), not only cementation, occurred at depth.

In core, a key isochron age from a fluorite-bearing fracture that postdates several types and stages of mineral-filled vugs (dissolution pores) provides evidence that substantial dissolution had...
occurred in Middle Ordovician carbonates by the end of the Devonian. We present a geological model based on our data and reported structural, petrological, geochemical, geophysical, petrophysical, radiometric and kinematic findings to show the evolution of the mechanisms and timing of dissolution that led to the formation of cavities in the Yijianfang Formation. The estimated fault-related porosity volume is at least 0.5%, which is augmented by fault-related mesogenetic dissolution and fault-transverse extension.

**Geological setting**

The Halahatang oilfield is part of the Tabei Uplift, one of the most prolific hydrocarbon accumulation zones in the Tarim Basin (Li et al. 1996; Jia 1997; Pang et al. 2010) (Fig. 1). The Tabei Uplift has the largest proven oil/gas reserves of the Tarim Basin with over 3 billion tons oil-equivalent (c. 21.5 billion barrels oil-equivalent) discovered in Ordovician carbonate rocks currently at 6000–7000 m depth (Zhu et al. 2016). Recently, giant oil accumulations have been discovered in the lower Paleozoic section at depths >8000 m (Zhu et al. 2019).

The Tabei Uplift is an inherited structural high formed on the pre-Sinian metamorphic basement (Zou 2012; Zhu et al. 2013a). This area experienced Sinian–Ordovician rifting during the Caledonian orogeny, followed by Silurian–Permian uplift during the Hercynian orogeny (290–250 Ma), transition into a foreland basin (forebulge) in the Triassic–Jurassic during the Indo-China orogeny, Cretaceous–Neogene extension related to the Yanshan orogeny, and late Neogene–Quaternary rapid subsidence (foreland basin) during the Himalayan orogeny (Zhu et al. 2013b, 2017, 2019; Fig. 2). The Halahatang oilfield is located in the Halahatang Depression and it is bounded by the Luntai Fault to the north, the Shuntuoguole Low Uplift to the south, the Lunnan Low to the east, and the Yingmaili Low Uplift to the west (Zhu et al. 2012; Chang et al. 2013). Other important oilfields in the Tabei Uplift include the Tahe and Lunnan oilfields to the east (Chang et al. 2013) (Fig. 1).

During the Cambrian, dolomitic sequences with intercalated gypsum and salt layers were deposited in an array of half-grabens developed as a result of regional extension (Lin et al. 2012; Gao and Fan 2013) (Fig. 2). Throughout the Ordovician, thick reef and shoal deposits accumulated in intra-platform, platform-margin and slope environments in a series of uplifts (i.e. Tazhong–Bachu, Tabei uplifts) with intervening depressions (i.e. Kuqa, Awati, Manjiaer) (Li et al. 1996; Jia 1997; Kang 2003; Gao and Fan 2013). In the Late Ordovician, the carbonate platform was drowned and overlain by a thick section of deepwater continental shelf- and slope-facies of dark mudstone and carbonaceous mudstone. The Silurian–Devonian orogeny was characterized by widespread marine sandstone deposition in intracratonic contractional basins (Liu et al. 2013; Zhao et al. 2016), giving way to alternate marine–nonmarine deposition in the

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**Fig. 1.** (a) Simplified tectonic map of the Tarim Basin showing uplifts and depressions (after Zhao et al. 2014). Dashed lines mark boundaries of tectonic regions. Rectangle shows area with the selected 98 GPS stations between 77 and 81°E and between 39 and 44°N, from the northern Tarim Basin across the Tian Shan (after Zubovich et al. 2010). (b) Main oilfields in Halahatang Depression and Lunnan Uplift (after Chang et al. 2017a). 1, Halahatang; 2, Tahe; 3, Lunnan.
Carboniferous–Permian (Zhang et al. 1983; Liu and Xiong 1991). Almost continuous Paleozoic sedimentation was interrupted by sporadic volcanism, including the Permian flood basalt magmatism of the Tarim Large Igneous Province (e.g. Xu et al. 2014). From the Triassic to the Quaternary, the Tarim Basin has been dominated by terrestrial siliciclastic deposition (Jia et al. 1995).

Hydrocarbon reservoirs in the Tabei Uplift mainly occur in Middle Ordovician Yingshan and Vijianfang Formations in the Lunnan Low Uplift and Halahatang Depression areas (Zhu et al. 2016, 2017) (Fig. 1). Muddy limestones and mudstones of the Tumuxiuke Formations from the Triassic to the Quaternary, the Tarim Basin has been dominated by terrestrial siliciclastic deposition (Jia et al. 1995).

Fractures and vugs in core

In the carbonate reservoirs studied, porosity does not correlate with permeability (Zhu et al. 2019). Such rocks constitute Type 1 ‘fracture type’ and ‘dissolution vug–fracture type’ or ‘fracture–cavity’ reservoirs, with very low porosity and permeability where most of the reservoir permeability is controlled by fractures and vugs (Nelson 1985; Bagrantsvea et al. 1989). Based on petrological, cross-cutting, SEM-EDS, cathodoluminescence (CL), isotopic, and fluid inclusion thermometric and compositional analyses, Baqués et al. (2020) identified seven main groups of fractures (F) and associated vugs (V) in Halahatang Middle Ordovician carbonate core samples (group 1 oldest, group 7 youngest; Figs 2 and 3). Fractures and vugs were grouped on the basis of cross-cutting relationships, mineral fill and isotopic compositions irrespective of their orientations because individual fractures are highly variable in orientation so that the latter is not a good measure of timing (set) and/or type. Fractures show a spectrum of cement-fill degree that is dependent on size. Consequently, the conventional terms ‘vein’ and ‘joint’ are not helpful. We use the unambiguous descriptive term ‘fracture’ to refer to opening-mode fractures and specify the cement attributes where necessary.

The oldest group of fractures (F1) comprises bed-perpendicular and bed-oblique, compacted (distorted) fractures filled with calcite cement that grades from equant to palisade morphology (Fig. 3a). Some F1 fractures contain a small amount of internal yellow carbonate sediment. The second group of fractures (F2) consists of bed-perpendicular, oblique and subhorizontal fractures filled with blocky calcite (Fig. 3a). F3 fractures are bed-perpendicular and oblique, calcite and bitumen-filled (Fig. 3b), and may preserve as much as 20% partial open porosity in fractures c. 1 mm wide. A fourth group (F4) encompasses bed-perpendicular and oblique fractures filled with calcite ± bitumen ± minor late pyrite cement (Fig. 3c). Some F4 are partially corroded. F5 fractures are infilled by euhedral fluorite, barite, celestite and calcite cements in variable proportions, and are associated with calcite, celestite and/or calcite filled silica host-rock replacement (Fig. 3d). F6 fractures are calcite-filled (Fig. 3e) and show elevated 87Sr/86Sr isotopic ratios compared with the host rock. Finally, group 7 comprises bedding-oblique, stylolitic and sheared fractures (F7) containing insoluble residual material, bitumen, dolomite and sheared calcite cement (Fig. 3f). Some fractures in this category contain cement bridges and crack-seal textures indicating cementation synchronous with fracture opening (see Lander & Laubach 2015; Ukar & Laubach 2016; Baqués et al. 2020). The most widespread and abundant type of vugs (V3) are filled with calcite and bitumen, and are usually associated with F3 fractures, stylolites and V1 mottled fabrics, highlighting the connection between fractures and dissolution in these rocks (Fig. 3h and i). We did not observe vugs associated with F5 fractures, but based on the fact that this association is common for all other identified fracture and vug groups, V5 vugs are probable. Similar to vugs, stylolites, both bed-parallel and tectonic, are
ubiquitous and formed throughout the geological history of these rocks. All stylolites contain bitumen and some bed-parallel stylolites also contain dolomite and replacement silica (Fig. 3).

Highly variable, but generally high (>80°C) homogenization temperatures of fluid inclusions within fracture and vug cements, as well as high salinities (5–20% NaCl equiv.) indicate that fluid inclusions probably re-equilibrated with high-temperature burial fluids and do not provide information on the true temperature and depth of precipitation of the cements. Consequently, Baqué et al. (2020) determined fracture and vug cementation depths on the basis of stable isotopic analyses (Craig 1965; Machel 1999) assuming a geothermal gradient of 2.79°C per 100 m for the Tabei Uplift during the Middle Ordovician (Wang et al. 2014). Because cemented fractures and vugs are cross-cut by the next generation of filled fractures and vugs, the calculated depths of cement precipitation based on stable isotopic analyses represent dissolution depths. Host rock diagenesis, including mottled fabrics (V1), developed at <220 m, within the shallow burial diagenetic environment, whereas F1 fractures formed and were cemented near the surface within the marine–phreatic level. Group 2 fractures and vugs (F2, V2) developed within the shallow burial diagenetic environment (c. 220 m), group 3 within the intermediate burial diagenetic environment (c. 625 m) and group 4 within the deep burial diagenetic environment (c. 2000 m). Groups 5–7 are probably the result of reported hydrothermal activity in the area (e.g. Liu et al. 2017a,b) and Mg-rich fluid infiltration, and their depth is undetermined. All fracture and vug cements of group 3 (included) and younger contain primary inclusions of oil indicating the presence of hydrocarbons in the system at the time of their filling by cement.

Sm–Nd fluorite date from core
To decipher timing of fluorite mineralization in the Halahatang oilfield, we conducted Sm–Nd radiometric dating of fluorite, barite and calcite aliquots of one F5 fracture fill from core RP4 (Fig. 5). Fluorite typically contains elevated REE concentrations that may show sufficient variations in Sm/Nd ratios to allow dating using the isochron approach (Turner et al. 2003). The $^{147}$Sm/$^{144}$Nd ratios of the samples analysed range from 0.083 (calcite) to 0.14 (fluorite + calcite + barite; whole fracture). All five analysed samples plot in a linear array and yield an age of 400 ± 37 Ma, with an initial εNd value of 0.511566 ± 0.000025 (2σ, MSWD = 0.78) (Table 1; Fig. 5).

Fractures, faults and dissolution vugs in outcrop
Redissolved palaeokarst
Structural diagenetic features in outcrops in the Bachu–Keping Uplift region, western Tarim Basin (Fig. 1), share many
characteristics with Ordovician rocks in core from producing parts of the basin, although with some important differences. Karstic palaeotopography (karst towers and dolines) and cave-fill sediments (chaotic breccias and laminated cave-sediment fill) are present in the topmost section of the Yingshan Formation in the XikeEr outcrop, indicating that subaerial exposure and karstification occurred prior to deposition of unconformable Silurian red beds (Fig. 6a). Approximately 60 m below the unconformity, large polymictic breccia bodies are exposed. The breccia clasts consist of Ordovician carbonate clasts and the matrix consists of a reddish muddy to sandy sediment (Fig. 6b). Cave breccias and cave sediment fills show evidence of sedimentation and cementation in the vadose zone such as laminated and geopetal structures (Fig. 6c). Laminated cave-sediment fillings consist of non-luminescent to bright-red-luminescent subhedral calcite crystals (Fig. 6d). Silica and barite mineralization postdate calcite overgrowths. These phases probably reflect interaction with silica-rich fluids that percolated through overlying Silurian siliciclastic rocks or high-temperature fluids (Fig. 6e). The palaeokarst is affected by redissolution that is best developed on the top surface of the karstic system (karst towers) (Fig. 6f), forming vugs and cavities that are partially cemented by palisade calcite crystals that can be over 30 cm thick (Fig. 6g). Such vugs closely resemble those widespread in Halahatang cores. Oxygen and carbon isotopic analyses, especially the depleted values in $\delta^{18}O$ compared with cave-sediment fill and host-rock calcite overgrowths within cave infills and palisade calcite, indicate precipitation from higher-temperature fluids (Fig. 7; Table 2).
Porous and dissolution-enhanced faults

In the Yijianfang and Keping outcrops (Fig. 1), opening-mode fractures and centimetre- to decametre-scale faults are common (Figs 8 and 9). Crosscutting and abutting relations constrain a relative time sequence of the fractures. Calcite-filled fractures striking NNE–SSW are oldest, followed by east–west, NW–SE- and barren NNE–SSW-striking fractures (Fig. 8a and b). Thrust and strike-slip faults strike predominantly N–S and NE–SW, respectively (Fig. 8c and d). At the Yijianfang outcrop, NW–SE-striking opening-mode fractures (Fig. 9a) have primary porosity and secondary vugs and caves similar to those in the XikeEr outcrop. Secondary caves are infilled by fluorite, coarse crystalline calcite, and in some cases gypsum (Fig. 9b and c). Calcite δ18O and δ13C values within NW–SE fractures are similar to those of the host rock, indicating high rock–fluid interaction (Fig. 7). These stable isotopic makeup resemble those of Middle Ordovician marine carbonates. In contrast, NE–SW strike-slip faults have damage and fault-core zones of highly porous and slightly calcite-cemented fault breccias with as much as 30% remaining macroscopic porosity (point-count estimate) (Fig. 9d). Similar porous fault rocks are present along decametre-scale damage zones of NE–SW strike-slip faults in dolomitized Pengliaba Formation, within the Dabantagh outcrop (Fig. 9e and f). In these field examples, fault damage zones are several metres wide (Fig. 9e). The high-porosity rock is discontinuous over c. 10 m, but the finite size of the outcrop (tens of metres) precludes assessment of the continuity pattern.

Present-day strain rates

The India–Eurasia collision drives roughly north-south contraction in the Tarim Basin (e.g. Tapponnier and Molnar 1979; Heidbach et al. 2018). The northern Tarim Basin and the Tian Shan account for a considerable amount, perhaps as much as 50–60%, of modern convergence between India and Eurasia (Zubovich et al. 2010). The rate of deformation near the Tian Shan exceeds that in the Himalaya and Tibet, so the Tian Shan effectively marks the plate boundary between Eurasia and India.

The velocity gradient tensor we determined from global positioning system (GPS) data of Zubovich et al. (2010), (Appendix B) surrounding the Halahatang oilfield indicates that the minimum (most negative, most contractional) extension rate trends 174° and measures −36.5 nstrain a−1 (Supplementary material), comparable in magnitude with strain rates surrounding the Pacific–North America plate boundary in the California borderland (Shen et al. 2001). Positive extension rate occurs in the intermediate principal direction, trending 084° and measuring 7.9 nstrain a−1, and the maximum principal rate of extension is approximately vertical and measures 28.6 nstrain a−1.

Analysis was validated by comparing observed velocity data with calculated velocities (Fig. 10). Model velocity vectors match observed velocities within 2 mm a−1 (length of vectorial residual) at 94 out of 98 stations (Supplementary material; red rows highlight counter-examples).

Table 1. Isotopic analyses of fluorite-, barite- and calcite-bearing F5 fracture used for the calculation of an isochron age

| Sample | 143Sm/144Nd | ±2σ | 143Nd/144Nd | ±2σ | [Nd] (ppm) | ±2σ | [Sm] (ppm) | ±2σ |
|--------|-------------|-----|-------------|-----|------------|-----|------------|-----|
| RP4 10 WF | 0.10959 | 0.00207 | 0.511844 | 0.000014 | 1.090 | 0.004 | 0.197 | 0.004 |
| RP4-11 WF | 0.14148 | 0.00076 | 0.511939 | 0.000012 | 1.200 | 0.005 | 0.281 | 0.001 |
| RP4 10 B + C1 | 0.08657 | 0.00046 | 0.511798 | 0.000012 | 7.011 | 0.029 | 1.003 | 0.003 |
| RP4 10 B + C2 | 0.08331 | 0.00045 | 0.511783 | 0.000012 | 5.784 | 0.024 | 0.797 | 0.003 |
| RP4 10 B + C3 | 0.08681 | 0.00046 | 0.511793 | 0.000012 | 7.066 | 0.029 | 1.014 | 0.003 |

Discussion

Bright spots, bit drops, cavities and faults

Ordovician carbonate rocks in the Tabei Uplift have been described as thoroughly karsted (Wang et al. 1992; Gu 1999; Liu et al. 2004; Zou et al. 2009; Zeng et al. 2011a) on the basis of sudden increases in drilling rates, bit drops, blowouts and mud loss (Tian et al. 2016). In the Tahe oilfield, such drilling abnormalities have been encountered in c. 39% of the total number of wells (He et al. 2010; Tian et al. 2016). Bit drops of c. 1 m are common in central (Tazhong) and northern Tarim Basin (Tabei; HA8, 2 m; HA9,
1.5 m; Yang et al. 2012) and some recorded bit drops in the Tabei Uplift are tens of metres (Yang et al. 2012; Zhao et al. 2014). Mud and drilling fluid losses before well completion may be upwards of 2300 m³ (Zhao et al. 2014; Tian et al. 2016).

Yingshan and Yijianfang Formations in northern and central Tarim Basin are characterized by areas of anomalously high-amplitude seismic reflections (bright spots) at c. 4000–6500 m depth (Zeng et al. 2011a, b; Zhao et al. 2014; Zhu et al. 2017; Yang et al. 2018) and the presence of bright spots has recently been confirmed in superdeep (>8000 m) Paleozoic reservoirs in southern Halahatang (Zhu et al. 2019). Bright spots are reflective of hydrocarbon-filled cavities that cause bit drops (Zeng et al. 2011a; Yang et al. 2018; Zhu et al. 2019). Such cavities have been inferred to be the main source of hydrocarbon storage and permeability and are the main target for exploration (Yang et al. 2012; Zhao et al. 2014; Zhu et al. 2014) with more than 80% success rate (Zeng et al. 2011a).

Many researchers have interpreted such cavities to be the result of palaeokarst (shallow or epigenetic dissolution) (e.g. Tian et al. 2017; Xu et al. 2017; Zhang et al. 2018). Cavities having such an origin are typically marked by dissolution, sediment fillings, chemical precipitates and localized fracturing, brecciation and collapse of cave walls and ceilings (Loucks 1999). In oilfields east of Halahatang (Tahe, Lunnan), reservoirs with well-attested palaeokarst features are widespread (Gu 1999; Liu et al. 2004; Zeng et al. 2011a; Zhao et al. 2014). In the Lunnan field, karst features occur mainly in the subsurface Yingshan Formation, which is overlain directly by Carboniferous siliciclastic rocks (Zeng et al. 2011a; Zhao et al. 2014), indicating a strong association of the karst is found with the unconformity. Evidence of collapsed and filled caves are found in outcrops or strata in the reservoir interval, for example, near Keping, where Ordovician carbonates are also directly overlain by Silurian red beds (Fig. 6a).

Few large caves have been documented below 3 km, an observation that previously led some workers to conclude that significant shallow palaeokarst cavities would not survive deep burial (Loucks 1999). Evidence for substantial cavities in what are clearly palaeokarst structures (e.g. Gao et al. 2018) shows that cavities do persist at depth. Also, rock tests and geomechanical modelling show that cavities can be stable under great loads, even in the absence of overpressure (e.g. Davis et al. 2017). Together, these considerations show that shallow palaeokarst is a plausible explanation for the cavities encountered in the Halahatang oilfield. Other evidence, however, suggests a more nuanced interpretation of cavities in the Halahatang oilfield. With the exception of the northernmost part of the area, a pervasive unconformity with Silurian siliciclastic rocks is absent in the palaeo-structurally lower Halahatang, indicating that subaerial exposure was short-lived and vadose–phreatic cave formation less likely compared with the up to 120 myr hiatus to the NE (Liu et al. 2004; Zeng et al. 2011a; Zhao

![Fig. 6.](http://jgs.lyellcollection.org/) (a) Outcrop photograph showing karstic palaeotopography (karst towers and dolines) and collapse deformation structures, and karstic chaotic breccias present on the topmost section of the Yingshan Formation in the XikeEr outcrop. Silurian red beds unconformably overlie Ordovician carbonates, indicating subaerial exposure. (b) Polymeric breccia bodies exposed c. 60 m below the unconformity. (c) Cave-sediment fill showing laminated sediments and geopetal structures evidencing their deposition in the vadose zone. (d) Laminated cave-sediment fillings showing non-luminescent to bright-red-luminescent concentric calcite overgrowths as seen under optical cathodoluminescence (CL). (e) Silica and barite mineralization postdating calcite overgrowths. (f) Redissolution cavities and calcite precipitated in cavities developed at the top surface of the karstic system (karst towers). (g) Palisade calcite crystals, over 30 cm thick, precipitated in the remaining open porosity of the redissolved cavities.
Deep-seated dissolution in the Halahatang oilfield

In outcrop, many NNE- and NNW-striking fault zones comprise porous fault rock, and dissolution along fractures formed caves lined with calcite and minerals precipitated from deep-sourced fluids (Fig. 9). Dissolution-enhanced fault rocks have been reported in core in the Halahatang area (Wu et al. 2019a). Both porous fault rock and dissolution-enhanced cavities could provide hydrocarbon storage and migration pathways in the subsurface. Based on the fragile character of the fault rock in outcrop, we infer that a bit encountering brecciated material in fault damage zones would sustain little resistance so drilling response might be indistinguishable from a cavity-related bit drop. Both types of structure could be associated with the observed large drilling mud losses. Based on the association between small-scale vugs and fractures and metre-to-decimetre-scale fractured zones with open cavities observed in core and image logs (Fig. 4), we interpret these dissolution-enhanced features to be the small-scale equivalents of fractured zones and open cavities responsible for bright spots and bit drops.

Corrosive agents such as acidic fluids associated with sulfur-rich oil, hydrothermal fluids, CO₂-rich fluids derived from underlying strata, meteoric waters or a combination of these could migrate along fractures and faults and form the dissolution cavities observed in core and inferred from seismic data, FMLs and production data. Away from faults, such fluids would flow laterally, along the unconformity with overlying, impermeable Tumuxiuke Formation. A combination of these processes, fault-parallel and lateral flow, provides an explanation for bright spots localized along the Ordovician unconformity (Wu et al. 2019b) as well as those that penetrate as far down as 800 m into the Yingshan Formation (Yang et al. 2018; Zhu et al. 2019).

Based on our GPS analyses, Andersonian mechanics predict ideal movement on orthonthorhombic faults having mixed strike-slip kinematics (Reches and Dieterich 1983). Steeply dipping fractures that strike parallel to the Tian Shan (Figs 1 and 11a) should show rapid present-day horizontal contraction, whereas steeply dipping fractures at high angle to the Tian Shan should show active extension. Conjugate components of strike-slip movement probably accompany both. Thus, our GPS analysis predicts that active movement on steeply dipping discontinuities having both NNE and NNW strikes, the main orientations of pre-existing faults in Halahatang (Fig. 11a), is extensional if not actively opening.

The calculated strain tensor agrees with in situ stress measurements at c. 7 km depth in the central part of the Tarim Basin south of our study area, which show that maximum extension is vertical (Sun et al. 2017). In contrast to both, vertical maximum compression is typical of modern (non-tectonic) sedimentary basins, but here we address an ancient (although now tectonic) sedimentary basin. Stress maps show north–south compression (e.g. Heidbach et al. 2018). Sun et al. (2017) reported in situ orientations of minimum compression c. N140°–N170°, which would cause active extension along NNE-striking faults. Rapid (recent and current) tectonic extension along high-angle pre-existing faults in strong Ordovician carbonate rocks could lead to formation of wide extension fractures, especially near releasing bends of faults, such as those documented in carbonate rocks in Oman (e.g. Hilgers et al. 2006; Holland and Urai 2010). If rate of opening movement exceeds the rate at which chemical processes can fill voids (calcite cementation) and/or if dissolution prevails in fractures, porosity and permeability along fractures are likely to persist and increase through time.

Cavity formation by protracted deep-seated dissolution

Because observations at Halahatang are inconsistent with palaeokarst formed in the shallow subsurface, an effective geological model for the mechanisms and timing of dissolution that led to the formation of cavities is necessary to guide exploration. Below we present a model of the geological evolution of the Yijianfang...
Table 2. Stable isotopic analyses

| Sample type                      | Outcrop | Formation | Mineralogy | δ^{13}CVPDB | δ^{18}OVPDB |
|----------------------------------|---------|-----------|------------|-------------|-------------|
| Yinshan Fm                       | XikeEr  | Yingshan  | Calcite    | 0.19        | −6.54       |
| Yinshan Fm                       | XikeEr  | Yingshan  | Calcite    | 0.36        | −6.39       |
| Laminated cave-sediment fill     | XikeEr  | Yingshan  | Non-pure calcite | 0.33      | −5.11       |
| Calcite overgrowth               | XikeEr  | Yingshan  | Non-pure calcite | −1.13     | −9.92       |
| Calcite cement in NNE–SSW fractures | Keping | Yijianfang | Calcite    | −1.17       | −9.08       |
| Calcite cement in N–S faults     | Yijianfang | Lianglitage | Calcite    | 0.14        | −5.71       |

Fig. 8. (a) Cross-cutting relationships between opening-mode fractures in the Yijianfang outcrop. (b) Late, barren NNE–SSW fractures. (c) NE–SW-striking thrust fault carrying Middle Ordovician Yijianfang Formation over Upper Ordovician Lianglitage Formation (Yijianfang outcrop) (Fig. 1). (d) Core of NE–SW strike-slip fault (Yijianfang outcrop).
Formation reservoir that integrates petrological, structural, geochemical, geophysical, petrophysical, temporal (cross-cutting relations and Sm–Nd isotopic dating), outcrop analogue and kinematic evidence summarized in this study.

The Yingshan and Yijianfang Formations were deposited in inner and middle-shelf to outer-shelf environments (Lin et al. 2012). During the middle Caledonian orogeny that resulted from the collision of the Kunlun island arc and the Tarim plate (Yu et al. 2011), uplift and erosion caused subaerial exposure of the Yijianfang Formation and an angular unconformity with the overlying Tumuxiuke Formation (Lin et al. 2012). In the Halahatang area, subaerial exposure was short-lived, resulting in the absence of penetrative palaeokarst in our study area. Instead, incipient dissolution with minor infiltration of soil sediment (V1) and F1 fractures (group 1; Fig. 3a and h) developed near the surface within the marine–phreatic environment at this stage (Figs 12 and 13a).

Renewed uplift during the middle Caledonian orogeny was succeeded by a disconformity between the Lianglitage Formation and overlying Sangtamu Formation (Fig. 2) following deposition in a low- to moderate-energy environment (Lin et al. 2012; Zhao et al. 2014). The western part of the Tabei palaeo-uplift experienced a notable, regional angular unconformity and a network of caves and karstic breccias that are absent at Halahatang (Baqués et al. 2020). Group 2 fractures and vugs (Fig. 3a and b) formed during burial and compaction and cements precipitated from marine to formation fluids in the marine to shallow burial environment (c. 220 m) (Fig. 13b). At least some F2 probably follow similar orientations to Caledonian faults, striking NNE and NNW (Cai et al. 2015).

Fig. 9. (a) NW–SE-striking opening-mode fractures (Yijianfang outcrop) with secondary caves filled with fluorite and coarse-crystalline calcite and in some cases gypsum. (b) Plane-light optical photomicrograph showing fluorite and calcite cements precipitated in cavities. (c) Plane-light optical photomicrograph showing palisade gypsum cement precipitated along a fracture wall. (d) NE–SW strike-slip faults showing damage zones and fault cores of highly porous and weakly calcite-cemented fault breccias with as much as 30% residual porosity (Yijianfang outcrop). (e) Decametre-scale damage zones of NE–SW strike-slip faults in dolomitized Pengliaba Formation within the Dabantagh outcrop. (f) Porous fault rocks along damage zones.
Following uplift, the Early Silurian sedimentary environment changed to nearshore and shallow-marine deposition. The first oil and gas accumulation phase occurred at this time (Lu et al. 2008b; Wang et al. 2008) (Fig. 12). Oil and gas migrated northward along unconformities and through faults and accumulated preferentially within Late Caledonian anticlinal traps (Zhu et al. 2013b). Fluids, including hydrocarbons and acidic fluids associated with sulfur-rich oil, flowed along group 3 fractures as indicated by the presence of oil inclusions in fracture calcite cement (Baqués et al. 2020), and laterally within Middle Ordovician strata, causing localized dissolution and formation of group 3 vugs and caves (Fig. 3b, 3h and 3i). Dissolution caused enlargement of dissolution-prone pre-existing mottle fabrics. Calcite cements precipitated in fractures and vugs from formation fluids in the intermediate burial realm (c. 625 m).

An unconformity formed in the Devonian during the Early Hercynian orogeny (Li et al. 2010; Chen et al. 2012) leading to extensive karstification of Ordovician strata in the nearby Tahe and Lunnan oilfields (Li et al. 2011; Yan et al. 2011; Yang et al. 2014; Tian et al. 2016; Fig. 1). In the Halahatang area, the Yijianfang and Yingshan Formations remained buried (c. 500–1000 m) and no widespread subaerial karst developed. Fluids circulated along Early Hercynian strike-slip faults and group 4 and 5 fractures (Fig. 3c to 3f). Owing to the impermeable nature of the Tumuxiuke Formation, fluids localized within Middle Ordovician strata flowed laterally, causing further dissolution and enlargement of vugs and caves and precipitation of calcite cements within the deep burial environment (c. 2000 m; Baqués et al. 2020) (Fig. 13d). Corrosive fluids associated with precipitation of pyrite and/or fluorite (Esteban and Taberner 2003) most likely caused partial dissolution of F4 fractures.

The Sm–Nd age we report indicates that fluorite-bearing fractures (F5; Figs. 3d and 5a) filled at this time. Fluorite and other minerals precipitated from high-temperature fluids present in cores in the Central Uplift (Tazhong; Fig. 1) and in outcrop in the Bachu–Keping region (Fig. 9b) are thought to be linked to widespread Permian magmatic activity (Jin et al. 2006; Wang et al. 2015) or to low-temperature meteoric circular hydrothermal fluids in the late Yanshanian–Himalayan (Zhang et al. 2006), but this radiometric age indicates that fluorite is younger at Halahatang. Our dated fluorite cement confirms that widespread mesogenetic dissolution cavities (V2–V4; Fig. 3b, c, h and e) existed in Middle Ordovician carbonates by the end of the Devonian (Figs 2 and 13c, d).

In the Carboniferous, regional unconformities formed between the Carboniferous and underlying Silurian–Devonian strata in the Manjia-er and Tabei area (Lu et al. 2008a; Zhu et al. 2012; Fig. 1). Fluvial and lacustrine facies were deposited in an interior basin setting (Zhu et al. 2012). Further cementation of previously formed fractures and vugs probably occurred at this time.

The Permian was a period of extensive magmatism, both extrusive and intrusive, in NW Tarim Basin (Yang et al. 2007; Tian et al. 2010; Xu et al. 2014; Shangguan et al. 2016) as well as associated normal faulting especially in the middle Permian (Liu et al. 2017b). Cements in group 6 fractures and vugs (Fig. 3c) show depleted δ18O and δ13C and high 87Sr/86Sr similar to those reported for Permian magmatism consistent with precipitation from Permian hydrothermal fluids of igneous origin (Baqués et al. 2020) (Fig. 13e).

In the Hercynian (Permian), Early–Middle Ordovician source rocks entered the maximum hydrocarbon generation window in the south of the Tabei area (Zhang et al. 2004; Zhang and Luo 2011;
Deep-seated dissolution in the Halahatang oilfield

Zhu et al. 2013a, b, 2017; Ge et al. 2020; Fig. 12). This was the main period of hydrocarbon generation and expulsion from Cambrian–Ordovician source rocks in the Tarim Basin (Li et al. 2010; Ge et al. 2020). Oil migrated from the south to the north and infilled previously formed vugs and cavities (Fig. 13c). In the latest Permian to earliest Triassic, thrust faults that penetrate pre-Jurassic strata developed (Liu et al. 2017a). This new episode of reactivation along pre-existing faults probably caused further milling of porous fault rock within fault damage zones, similar to that present in outcrop (Fig. 9e and f), so that the rocks became prone to hydrocarbon storage. Main oil pools in Ordovician rocks were formed in the Permian (Zhu et al. 2013a; Ge et al. 2020) so that Hercynian tectonism is crucial to petroleum generation and accumulation in the Tarim Basin.

Following terrestrial sediment deposition in the Triassic (Lin et al. 2012; Zhu et al. 2013b), and uplift related to the late Indosinian orogeny (Tang et al. 2014; Zhao et al. 2014), two regional unconformities formed as a result of the Yanshanian orogeny at the end of the Jurassic (Middle Yanshanian) and at the end of the Cretaceous (Later Yanshanian) (Tang et al. 2014) (Fig. 2). Although Meso-Cenozoic thrust faults dominate (Zhang et al. 1996; Sobel and Dumitru 1997; Yin et al. 1998; Bullen et al. 2003; Meng et al. 2008; Li et al. 2009, 2010; Zheng et al. 2009), the Tarim Basin also experienced local extension in the Jurassic–Early Cretaceous when maximum compression was NE–SW, forming left-lateral ENE and right lateral north–south transpressional fault zones (Li et al. 2013). Under NNE–SSW maximum principal compression ($\sigma_1$) (Li et al. 2013), pre-existing faults in this orientation would have experienced opening, providing further volume for hydrocarbon storage. Group 7 sheared fractures (Fig. 3f) and tectonic stylolites and stylobreccias (Baqués et al. 2020) most probably formed associated with this faulting, probably during a period of Mg-rich fluid upwelling as indicated by the presence of dolomite (Baqués et al. 2020) (Figs 12 and 13f).

In the Late Cretaceous–late Cenozoic, conjugate NNE-striking right-lateral and east–west-striking left-lateral transpressional fault zones formed in the Tabei Uplift (Li et al. 2013) whereas the direction of maximum compression was NE–SW during the Himalayan orogeny (Guo 1993; Sobel and Dumitru 1997; Li et al. 2001). Pre-existing faults that strike NW–SE were reactivated in extension at this time (Li et al. 2013). Driven by thick Cretaceous–Tertiary accumulations derived from the Tian Shan, Mid- to Late Ordovician strata in the Halahatang Depression entered the hydrocarbon generation window, leading to a second phase of hydrocarbon charge (Chang et al. 2013) (Fig. 12). Hydrocarbons migrated from the south to the north along faults and possibly also unconformities (Lu et al. 2008b). During the Pliocene–Quaternary, the Halahatang Depression experienced rapid burial (Zhu et al. 2017). South of the study area, Cambrian-sourced oil remains uncracked because the residence time at temperatures greater than c. 150°C has been relatively short (Zhu et al. 2018, 2019).

Consistent with Heidbach et al. (2018), our velocity-gradient tensor analysis shows that at present day, the maximum rate of contraction is oriented roughly north–south and absolute extension persists along both steeply dipping fault orientations (NNE–SSW and NNW–SSE) that dominate in the study volume (Fig. 11a). Progressive extension allows large cavities along faults to enlarge and stay connected at depth (Fig. 13g). Near-vertical fissures formed under current conditions would connect pre-existing pores, vugs and caverns along faults and enhance reservoir permeability, especially near releasing bends that evolved during fault segment linkage. Growth of the fracture network may have been promoted by the corrosive fluids (Laubach et al. 2019). Although in northern Halahatang normal pressure systems indicate a well-developed fracture–cavity system, to the south, moderate overpressures with high pressure coefficients indicate that cavities remained isolated and with low connectivity (Zhu et al. 2019).

Porosity estimate

As a rough proxy for porosity along faults, we inferred opening strain accumulated by major (mapped) faults in the Halahatang area along an east–west scanline across the study area (Fig. 11). Both NNE- and NNW-striking faults were included under the assumption that they are equally likely to contribute to fault-related strain. Field observations (Fig. 9c) and subsurface mapping (Wu et al. 2019b)

Fig. 12. Estimated timing and depths of formation of Groups (G) 1–7 fractures and vugs in the context of a burial history model calculated for one of the wells in our studied area (see Fig. 11a).
document that these faults have cores of considerable width. We measured porous fault cores and damaged zones of 2.5 m for small-displacement (>10 m) faults (Fig. 9e). Longer faults may have fault damage zones of up to 1100 m based on inferences from seismic and production data by Wu et al. (2019). The relationship of fault core width to fault length, if there is one, as reported by many researchers (e.g. Walsh and Watterson 1987; La Bruna et al. 2018; Scholz 2019), is unknown. As a crude approximation, we assumed that the fault length (in kilometres) corresponds to a fault-core width (in metres) (see Robertson 1983; Scholz 1987; Hull 1988; Marrett and Allmendinger 1990, and references therein). Fracture strain was calculated as the sum of fault core widths divided by the length of the scanline. Calculated fault-related strain is 0.4% (Table 3). This is a minimum estimate because only major faults were taken into account; addition of smaller, unmapped faults and faults that are below seismic resolution would increase, perhaps even double, this estimate. Porosity was assumed to be as much as 30% of the fault material on the basis of limited examples from outcrop (Fig. 9d–f). This estimated fault porosity is within the mid to high end of the estimated volume of rock occupied by unconfined caves in carbonate aquifers (0.004–0.48%) (Worthington 1999; Worthington et al. 2000; Klimchouk 2006) and low end of those occupied by confined caves (c. 1–5%) (Heward et al. 2000; Klimchouk 2006; Albert et al. 2015) in both shallow and deeply buried, collapsed karst (0.3–3%) (Weber and Bakker 1981, and references therein). Reported porosity in Paleozoic reservoirs of the Tarim Basin (including karst) is 5–12% (Gu et al. 2002), suggesting that mesogenetic dissolution and mechanical openings such as releasing bends along faults increased, by at least 10 times, total reservoir porosity.

Conclusions

Large cavities associated with high oil production and decametre-scale bit drops in the Halahatang oilfield have been ascribed to shallow (epigenetic) dissolution and well-developed palaeokarst that governs production from other Ordovician carbonate rocks in the Tabei Uplift, where subaerial exposure during the Hercynian orogeny was comparatively long lived. However, for the Halahatang oilfield rocks, cavernous porosity probably formed at depths of c. 220–2000 m as a result of the flow of organic acidic, high-temperature formation waters, and Mg-rich corrosive fluids along fractures and especially faults. Core observations of open and filled vugs and fractures show that the Halahatang area experienced several stages of fracture and associated dissolution marked by multiple generations of crosscutting fractures and vugs (large pores) containing cements with distinct petrological, isotopic and geochemical characteristics.
Cemented fractures and vugs are cut by subsequent generations of structural diagenetic features indicating that episodes of both dissolution and cementation occurred at mesogenetic depths. Based on O–C isotopic values, and linking values to thermal history, vugs may have formed at depths as great as 2 km. A Sm–Nd isochron age of 400 ± 37 Ma for fracture-filling fluorite indicates that some vugs and possibly associated dissolution-enhanced fault zones formed prior to the attested main period of hydrocarbon generation and expulsion in the late Hercynian (Permian). A complex tectonic history resulted in multi-stage reactivation of faults both in shear and extension, and formation of porous fault rock and dissolution-enhanced cavities, as evidenced by fault rocks exposed in nearby outcrops. Estimates based on fault porosity and abundance and core observations suggest that mesogenetic porosity enhancement of as much as 5–10% is locally plausible. Values are probably much lower averaged over the entire Halahatang structure. Both porous fault rock and dissolution-enhanced cavities and fractures could provide hydrocarbon storage and migration pathways and be responsible for decametre-scale bit drops and large volumes of drilling mud losses.

We used published GPS data to estimate deformation rates. Analysis indicates that, in agreement with previous work, the main faults in the Halahatang area (striking NNE–SSW and NWW–SSE) currently experience extension. Rapid extension promotes open fractures connecting pre-existing pores, vugs and caverns.

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Author contributions. EU: conceptualization (lead), data curation (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (lead), supervision (lead), writing – original draft (lead); VB: conceptualization (equal), data curation (lead), formal analysis (lead), investigation (equal), methodology (equal), writing – review & editing (supporting); SEL: conceptualization (supporting), formal analysis (supporting), funding acquisition (equal), methodology (supporting), writing – review & editing (supporting); RM: conceptualization (supporting), formal analysis (supporting), writing – original draft (supporting).

Data availability statement. All data generated or analysed during this study are included in this published article (and its supplementary information files).

Scientific editing by Robert Holdsworth.

Appendix A: Methods

Fieldwork was conducted in the Bachu–Keping Uplift region in the western Tarim Basin. A total of 36 oriented carbonate rock samples were collected from the Dabantagh, Yijianfang, XikeEr and Keping outcrops (Bachu Uplift, NW Tarim Basin) (Fig. 1).

Five fracture-filling fluorite, barite and calcite mineral separates and whole-fracture aliquots from core RP4 were crushed to fine-grained powders in an agate mortar for radiometric dating. Mineral separates and whole-fracture powders were spiked with a mixed 150Nd–149Sm spike and dissolved in alternating rounds of nitric acid, aqua regia, and boric acid on a hotplate at 150°C at the class 100 Radiogenic Isotope Clean Laboratory, The University of Texas at Austin. All reagents used were either optima grade or double distilled. Dissolution steps were repeated multiple times to achieve complete decomposition of more resistant mineral phases (barite and fluorite). Rare earth elements (REE) were isolated using column chromatography by means of BioRad RE-Spec resin and nitric acid. Sm and Nd were isolated from the REE fractions using BioRad LN Spec and dilute hydrochloric acid.

Nd and Sm separates were analysed by thermal ionization mass spectrometry on a Triton system using double rhenium filaments. An in-house macro was used to deconvolve the spike. The Excel macro contains the spike information and iteratively corrects for spike and analytical mass bias until the corrections converge on the same value. Averages were calculated using Isotop 4.

Aliquots of c. 0.3 mg were analysed for δ13C and δ18O using a ThermoFisher Scientific GasBench II coupled to a ThermoFisher Scientific MAT-253 isotope ratio mass spectrometer (Révész and Landwehr 2002; Spötl and Vennemann 2003) at The University of Texas at Austin. Samples were reacted in helium-flushed vials with 103% H3PO4 at 50°C for 3 h. Data were calibrated using calcite standards NBS-18 (δ18OVPDB = −23.0‰, δ13CVPDB = −5.0‰) and NBS-19 (δ18OVPDB = −23.3‰, δ13CVPDB = 1.95‰). Twelve replicates of an internal carbonate standard were analysed throughout the analytical session to account for analytical drift and precision. Analytical precision of ±0.06‰ for δ13CVPDB and ±0.10‰ for δ18OVPDB were routinely achieved.

Table 3. Mapped fault dimensions and calculated strain

| Distance east–west (km) | Fault trace length (km) | Average strike |
|-------------------------|-------------------------|----------------|
| 0.4                     | 4.04                    | NE             |
| 5.65                    | 14.79                   | NW             |
| 0.47                    | 5.64                    | NE             |
| 0.4                     | 10.97                   | NW             |
| 0.52                    | 2.58                    | NE             |
| 4.85                    | 7.77                    | NE             |
| 0.66                    | 3.84                    | NE             |
| 0.95                    | 6.1                     | NW             |
| 2.2                     | 7.3                     | NE             |
| 0.38                    | 2.51                    | NW             |
| 1.61                    | 6.22                    | NW             |
| 2.65                    | 7.19                    | NE             |
| 1.23                    | 2.38                    | NW             |
| 3.03                    | 2.27                    | NE             |
| 0.64                    | 15.07                   | NW             |
| 0.26                    | 2.53                    | NW             |
| 3.31                    | 1.26                    | NE             |
| 0.17                    | 6.26                    | NE             |
| 0.2                     | 2.21                    | NE             |
| 3.81                    | 10.52                   | NE             |
| 3.81                    | 21.52                   | NW             |
| 4.04                    | 5                      | NW             |
| 2.25                    | 8.65                    | NW             |
| 1.44                    | 2.33                    | NE             |
| 0.95                    | 17.25                   | NW             |
| 0.71                    | 6.47                    | NW             |
| 2.68                    |                         |                |
| 49.27                   | 182.67                  | Total          |
| L construed as aperture (m) | 182               |                |
| Scalenline length (m)     | 49452.67               |                |
| Strain                   | 0.0037                  |                |
To better quantify active deformation in the Halahatang oilfield, we analysed data published by Zubovich et al. (2010) from geodetic GPS stations \((N = 400+)\) representing 16 years of observations. We limited data geographically to an area comprising 98 GPS stations (Fig. 1) to constrain a least-squares estimate of the velocity gradient tensor, from which principal directions and magnitudes of strain rate were determined (Appendix B). Using the analysis, present-day kinematics were evaluated for orientations of faults and fractures observed in outcrop, and in wells and seismic data.

Appendix B: Velocity gradient tensor and principal direction and magnitude calculation method

For approximately homogeneous deformation, the velocity gradient tensor \((\nabla \mathbf{v})\) relates the vector from the coordinate origin to the location of a particle \((p)\) with the velocity vector \((\mathbf{v})\) of the same particle via matrix multiplication (Ramsay and Huber 1983; Allmendinger et al. 2012):

\[
\mathbf{v} = \nabla \mathbf{v} \cdot \mathbf{p}.
\]  

(B1)

Although the problem at hand is fundamentally three-dimensional, GPS data yield ineffective constraints in the vertical direction owing to large uncertainties that stem from satellite geometry. For this reason, we analyse only horizontal components of GPS data, and assume that the vertical is a principal direction of strain rate. The assumption is justified by the footprint of the geodetic network, which is large in comparison with both the amplitudes of surface topography and crustal thickness, so Anderson’s theory of faulting (Anderson 1951) predicts that the vertical should be a principal direction of stress. We apply equation (B1) in the horizontal plane, and ignore curvature of the Earth’s surface. Provided that the rate of crustal volume change is zero, principal strain rates in the horizontal plane yield a complementary estimate of strain rate in the vertical direction. Computation is simplified by demanding that \(v\) and \(p\) observations share not only coordinate system but also units of measure.

A local Cartesian coordinate system was defined by an origin located at the centre of mass for GPS receiver coordinates in the study area, at which point model velocity equals the average velocity among all GPS stations. Averages were subtracted from published values of \(v\) and \(p\), and all length units were converted to kilometres. If deformation is approximately homogeneous, then each GPS receiver (associated values of \(v\) and \(p\)) constitutes a partial constraint on a common velocity gradient tensor. In concert, the GPS dataset \((N=98)\) dramatically over-constrains the velocity gradient tensor, so we seek the unique solution that best fits the dataset in a least-squares sense. The sums of component-wise squares for residuals between model velocity \((\hat{v})\) and observed velocity \((v)\) were minimized across the scope of the dataset:

\[
\sum_{i=1}^{N} (v_x' - v_x)^2 = \sum_{i=1}^{N} (\nabla v_{x'x} \cdot p_x + \nabla v_{x'y} \cdot p_y - v_x)^2
\]

\[
\sum_{i=1}^{N} (v_y' - v_y)^2 = \sum_{i=1}^{N} (\nabla v_{y'x} \cdot p_x + \nabla v_{y'y} \cdot p_y - v_y)^2
\]

(B2)

where positive \(x\) and \(y\) signify geographical eastward and northward directions, respectively. Minimization was achieved by setting partial derivatives to zero for each component of the velocity gradient tensor, and solving the consequent system of four equations, which yields

\[
\nabla v_{x'x} = \frac{\sum p_x^2 \sum p_v v_x - \sum p_x p_v \sum p_v v_x}{\sum p_x^2 \sum p_v^2 - (\sum p_x p_v)^2}
\]

\[
\nabla v_{x'y} = \frac{\sum p_x^2 \sum p_v v_y - \sum p_x p_v \sum p_v v_y}{\sum p_x^2 \sum p_v^2 - (\sum p_x p_v)^2}
\]

(B3)

\[
\nabla v_{y'x} = \frac{\sum p_y^2 \sum p_v v_x - \sum p_y p_v \sum p_v v_x}{\sum p_y^2 \sum p_v^2 - (\sum p_y p_v)^2}
\]

\[
\nabla v_{y'y} = \frac{\sum p_y^2 \sum p_v v_y - \sum p_y p_v \sum p_v v_y}{\sum p_y^2 \sum p_v^2 - (\sum p_y p_v)^2}
\]

It should be noted that \(\nabla v_{x'x}\) and \(\nabla v_{x'y}\) are independent of \(v_y\), whereas \(\nabla v_{x'y}\) and \(\nabla v_{y'y}\) are independent of \(v_x\). The velocity gradient tensor is inherently asymmetric \((\nabla v_{x'y} \neq \nabla v_{y'x})\), so the anti-symmetric part quantifies average rotation rate about a vertical axis for the study area. The symmetric part of the velocity gradient tensor (i.e. strain rate tensor) quantifies distortional and dilational components of deformation, and excludes the rotational component (Ramsay and Huber 1983; Allmendinger et al. 2012). Based on assumption that the rate of volume change equals zero, the vertical rate of strain equals

\[
\nabla v_{z'z} = - (\nabla v_{x'x} + \nabla v_{y'y})
\]

(B4)

regardless of whether the vertical is a principal direction or not. If a principal direction is approximately vertical, then

\[
\nabla v_{z'z} = \nabla v_{x'x} = \nabla v_{y'y} = 0.
\]

(B5)

Conventional analysis of the velocity gradient tensor yields principal directions and rates of strain in all three spatial dimensions.

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