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Clip-off Chemistry: Synthesis by Programmed Disassembly of Reticular Materials**

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Abstract: Bond breaking is an essential process in chemical transformations and the ability of researchers to strategically dictate which bonds in a given system will be broken translates to greater synthetic control. Here, we report extending the concept of selective bond breaking to reticular materials in a new synthetic approach that we call Clip-off Chemistry. We show that bond-breaking in these structures can be controlled at the molecular level; is periodic, quantitative, and selective; is effective in reactions performed in either solid or liquid phases; and can occur in a single-crystal-to-single-crystal fashion involving the entire bulk precursor sample. We validate Clip-off Chemistry by synthesizing two topologically distinct 3D metal-organic frameworks (MOFs) from two reported 3D MOFs, and a metal-organic macrocycle from metal-organic polyhedra (MOP). Clip-off Chemistry opens the door to the programmed disassembly of reticular materials and thus to the design and synthesis of new molecules and materials.

Introduction

Throughout history, innovations in chemical synthesis have yielded previously inaccessible new molecules and materials that have enabled vast improvements in human life, ranging from fine chemicals to complex functional materials. Each new reaction and methodology not only help to expand accessible chemical space, but also inspire researchers to further innovate in the iterative design and preparation of new chemical targets of social, economic or industrial value. To date, most state-of-the-art synthetic

approaches use bottom-up strategies that, at the latter stage, mainly entail controlling the formation of new bonds. A relatively recent example of this is reticular chemistry,^[1–7] in which judiciously-designed, rigid molecular building blocks (MBBs) are linked by strong bonds to create crystalline open-framework materials^[8] such as metal-organic frameworks (MOFs),^[1–4] covalent-organic frameworks (COFs)^[9] and metal-organic polyhedra (MOPs).^[10–12] Reticular materials are a fascinating source of metal-organic and purely organic structures built up from an endless variety of fragments and MBBs^[13] (e.g. metal clusters, cages, cycles, metal layers, metal chains, etc.) that often do not exist in their isolated form.

We envisaged that by selectively breaking certain bonds in reticular materials, we could transform them into new frameworks or break them into new molecular fragments or isolated MBBs, as a synthetic strategy towards new materials and molecules. We hypothesized that we could use a chemical reaction for programmed bond-breaking, such that the de-reticulation process would occur at the molecular level. We reasoned that this would require the presence of cleavable groups at specific positions within the structures of the corresponding reticular materials, and that reported reticular materials that contain linkers featuring alkene bonds would be ideal starting materials for this strategy. However, we thought that, in the likely event that the targeted structure-precursor did not contain any alkene groups, we could generalize this approach to numerous reticular materials by inserting such groups into the pre-selected linkers without modifying their size or geometry, via reticular chemistry.

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Indeed, reticular chemistry dictates that for a given framework, the constituents can be chemically functionalized pre- and/or post-synthetically,^[14,15] without any loss to framework connectivity. Thus, we extended this concept to the ability to encode the organic linker of an existing MOF by inserting cleavable alkene groups into it, without modifying the linker size or topology, to ultimately enable assembly of the corresponding isorecticular MOF structures containing the desired cleavable group.^[16]

Herein we report a new synthetic approach, called Clip-off Chemistry, which is based on the programmed disassembly of reticular materials by controlled breaking of selected bonds. We validated Clip-off Chemistry by synthesizing two topologically distinct, three-dimensional (3D) MOFs from two reported 3D MOFs in single-crystal-to-single-crystal transformations. Through these examples, we demonstrated that reticular materials could be modified via cleavage, rather than formation, of bonds in their frameworks, enabling alterations to the connectivity of their constituent MBBs and therefore, to their topology. Next, we anticipated that Clip-off Chemistry could be generalized by applying it to 0-D molecular systems. To this end, we synthesized a novel metal-organic macrocycle from a MOP precursor. In all the examples we report here, we used ozonolysis as the chemical reaction to cut off constituent organic MBBs or linkers via direct cleavage of their alkene bonds.

Results and Discussion

Clip-off Chemistry is based on using, as starting materials, structures that contain cleavable groups (in this study, alkenes) at specific positions, such that cleavage of said groups generates new molecules or materials. Following this principle, we first targeted the clip-off synthesis of a new 3D MOF from a 3D MOF precursor. When selecting precursors in Clip-off Chemistry, reticular analysis of their underlying nets^[17–19] is important, as bond-breaking in the structure relates to disassembly of certain circuits of connections.^[20] In reticular materials this disassembly can be performed mainly by erasing some of the edges or nodes. Translating this analysis to the chemical field, the clip-off synthesis of a structure (here, a 3D MOF) from the disassembly of another structure (here, another 3D MOF) can be achieved by selecting either of two potential precursors: i) a structure built from one type of polytopic linker that contains different circuits of connections between the clusters, containing a cleavable bond in at least one of the circuits; or ii) a mixed-linker structure, in which linkers are located at different crystallographic positions, and one of them contains a cleavable bond. Cleavage of the polytopic linker will provoke disassembly of the circuits of connections in which the cleavable bond is involved, thereby forming a structure built up exclusively from those circuits that do not contain the cleavable groups, with a distinct underlying topology. Similarly, in the mixed-linker structure, cleavage of the linker containing the cleavable bond will provoke disassembly of the circuits of connections in which it is involved, thereby forming a structure built up exclusively from those circuits that involve

the metal clusters and the other linkers that do not contain the cleavable groups.

In our choice of precursor for the first 3D MOF synthesis, we followed the polytopic linker approach described above (Figure 1). Thus, we selected the Zr-**scu**-MOF,^[21] in which the assembly of eight-connected (8-c), quadrangular prismatic $Zr_6O_4(OH)_4$ clusters to 4-c rectangular linkers 5-[(3,5-dicarboxyphenyl)diazanyl]benzene-1,3-dicarboxylate (L_1) forms a 3D framework with a 4,8-c **scu/3,3,8T132** underlying topology^[22] and 1D channels (size: ≈ 7 Å) along one axis. However, as this reported structure does not contain any cleavable alkene groups, we had to insert them chemically, using the well-known isorecticular principle.^[16] This step of introducing cleavable groups into precursors can be performed before the cleavage step as needed, by replacing at least one of the original linkers with one of similar size and geometry that contains the desired cleavable groups at strategic positions. Once inserted into the isorecticular structure, such linkers generate different circuits of connections, in which at least one circuit contains the cleavable bonds. In our example, we replaced the linker L_1 with 5-[2-(3,5-dicarboxyphenyl)ethenyl]benzene-1,3-dicarboxylate (L_2), which contains olefinic bonds for cleavage. We thus synthesized an isorecticular Zr-**scu**-MOF framework built up from different circuits of connections, wherein only some of them contain the cleavable olefinic bonds of L_2 . We anticipated that, upon treatment of this framework with ozone,^[23–27] each 4-c L_2 linker would be split into two 2-c linkers (doubly deprotonated trimesic acid and/or 5-formylisophthalate). Consequently, only the circuits of connections between the $Zr_6O_4(OH)_4$ clusters and these 2-c linkers would remain, forming a Zr-**pcu**-MOF. In contrast to the isorecticular Zr-**scu**-MOF precursor, which is based on quadrangular prismatic 8-c Zr-clusters, each $Zr_6O_4(OH)_4$ cluster is still coordinated by 8 linkers in this new Zr-**pcu**-MOF, however its topological connectivity decreases from 8-c to a 6-c because two pairs of the eight 2-c linkers connect the same two clusters (Figure S2).^[28]

We expected that this first clip-off reaction would afford the first-ever example of a 3D MOF made of archetypical Zr-oxo-hydroxo-clusters linked by isophthalate-like linkers in a **pcu** underlying net. Interestingly, the closest literature example of such a structure is that of a 2D MOF made of Zr-oxo-hydroxo-clusters linked by isophthalate, albeit in an **hcb** topology.^[29] Our target 3D Zr-**pcu** MOF could also be seen as exemplifying a connection of Zr-oxo-hydroxo-clusters through trimesate linkers, which are coordinated only through two of their three carboxylate groups. Accordingly, it could also be considered as the first example of a Zr-structure with a free carboxylic acid using trimesate, as researchers have previously reported combination of Zr-oxo-hydroxo-clusters with this linker in a **spn** topology of 3,6-connectivity.^[30]

We synthesized colorless cubic crystals of isorecticular Zr-**scu**-MOF by solvothermal reaction (120 °C) of a mixture of $ZrOCl_2 \cdot 8H_2O$ and L_2 in *N,N*-dimethylformamide (DMF) and formic acid for 5 days. The crystal structure revealed the expected isorecticular **scu** framework, in which L_1 had been replaced by L_2 (Figure 2a; see Supporting Information (SI), section S2). Next, we confirmed the phase purity of the bulk

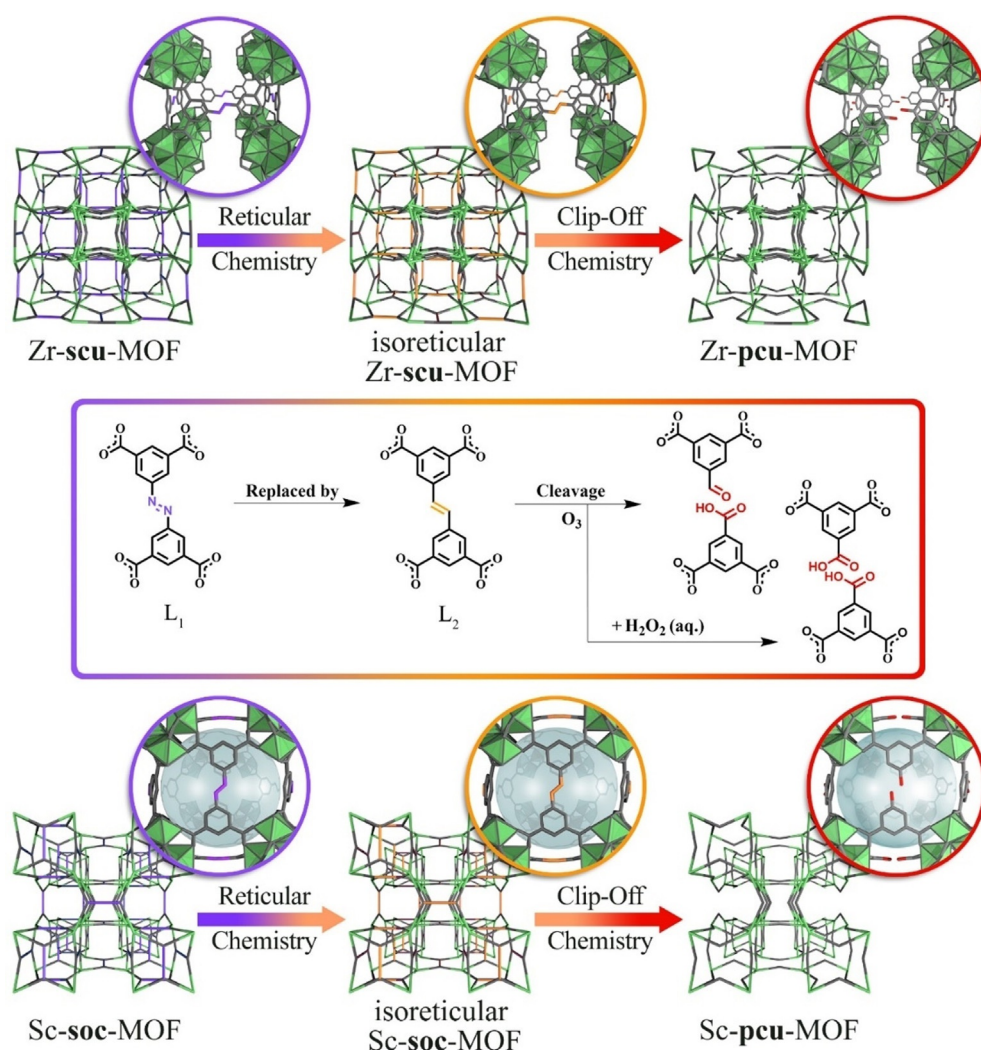


Figure 1. Clip-off Chemistry. Representative examples of Clip-off Chemistry, starting with the isoreticular insertion of cleavable (here, alkene) groups into a MOF structure,^[16] followed by the quantitative breaking of these cleavable groups by ozonolysis to afford a new structure. Top: clip-off synthesis of Zr-pcu-MOF from Zr-scu-MOF. Bottom: clip-off synthesis of Sc-pcu-MOF from Sc-soc-MOF. Middle: chemical reaction for both syntheses. The formation of aldehyde/carboxylic acid groups after ozonolysis is not shown in the lower magnification nets for better illustration of the breaking process. The formation of these groups is shown in the magnified structures, wherein the red groups represent aldehyde or carboxylic acid groups.

sample by X-ray powder diffraction (XRPD) and scanning electron microscopy (SEM) (Figures 2b, S3, S12).

We began the clip-off synthesis of Zr-pcu-MOF by packing 20 mg of synthesized Zr-scu-MOF crystals into a plastic tube, connected on one side to the ozonator (through a CaCl₂ humidity trap) and, on the other side, to a vacuum pump (through a KI trap), to ensure a continuous flow of ozone through the column.^[23,24] The reaction was run at room temperature for 30 min. Afterwards, the sample was connected to vacuum for another 30 min. This ozonation/vacuum cycle was repeated nine times for the complete cleavage of all the alkene bonds in Zr-scu-MOF, as evidenced by the gradual disappearance of the characteristic olefinic peak at 7.69 ppm in the ¹H NMR spectra of the digested Zr-scu-MOF crystals (vide infra; Figure S8). After nine cycles, the resulting solid

was directly collected from the tube and stored in tetrahydrofuran.

Next, we characterized the ozonated Zr-scu-MOF crystals by single crystal X-ray diffraction (SCXRD), which confirmed that they had retained the single-crystal character (Figures 2c, S1, S2). For these crystals, synchrotron diffraction data were collected at a maximum resolution of 1.2 Å. Data analyses revealed a variation in the lattice parameters, as compared to the pristine structure. Both pre- and post-ozonolysis crystal structures were solved in the monoclinic *C2/m* space group. However, the cell volume of the ozonated crystal was found to be 16076.00(10) Å³, whereas that of the pristine Zr-scu-MOF was 16957.46(10) Å³. Analysis of the diffraction data demonstrated the integrity of the inorganic secondary building units (SBUs, metal and carboxylate atoms) were assigned and anisotropically refined. As for the rest of the organic linker, carbon atoms belonging to the

phenyl ring were located in the difference electron density maps. However, their high thermal parameter values indicated a possible positional disorder. Moreover, the olefinic carbon atoms could no longer be located, supporting the completeness of the ozonolysis reaction. This is in stark contrast to the pristine MOF, in which the positions of these atoms were clearly visible and refined. The position of the resulting aldehydes or carboxylic groups, newly inserted in the MOF upon cleavage of the carbon-carbon double bond, could not be determined from the analysis of the difference electron density maps. Instead, a large residual electron density was observed in the vicinity of the positions that were initially occupied by the olefinic group. When comparing the two structures, additional differences could be observed in the arrangement of other framework atoms. Most notably, the relative orientation of opposite phenyl rings in a same linker

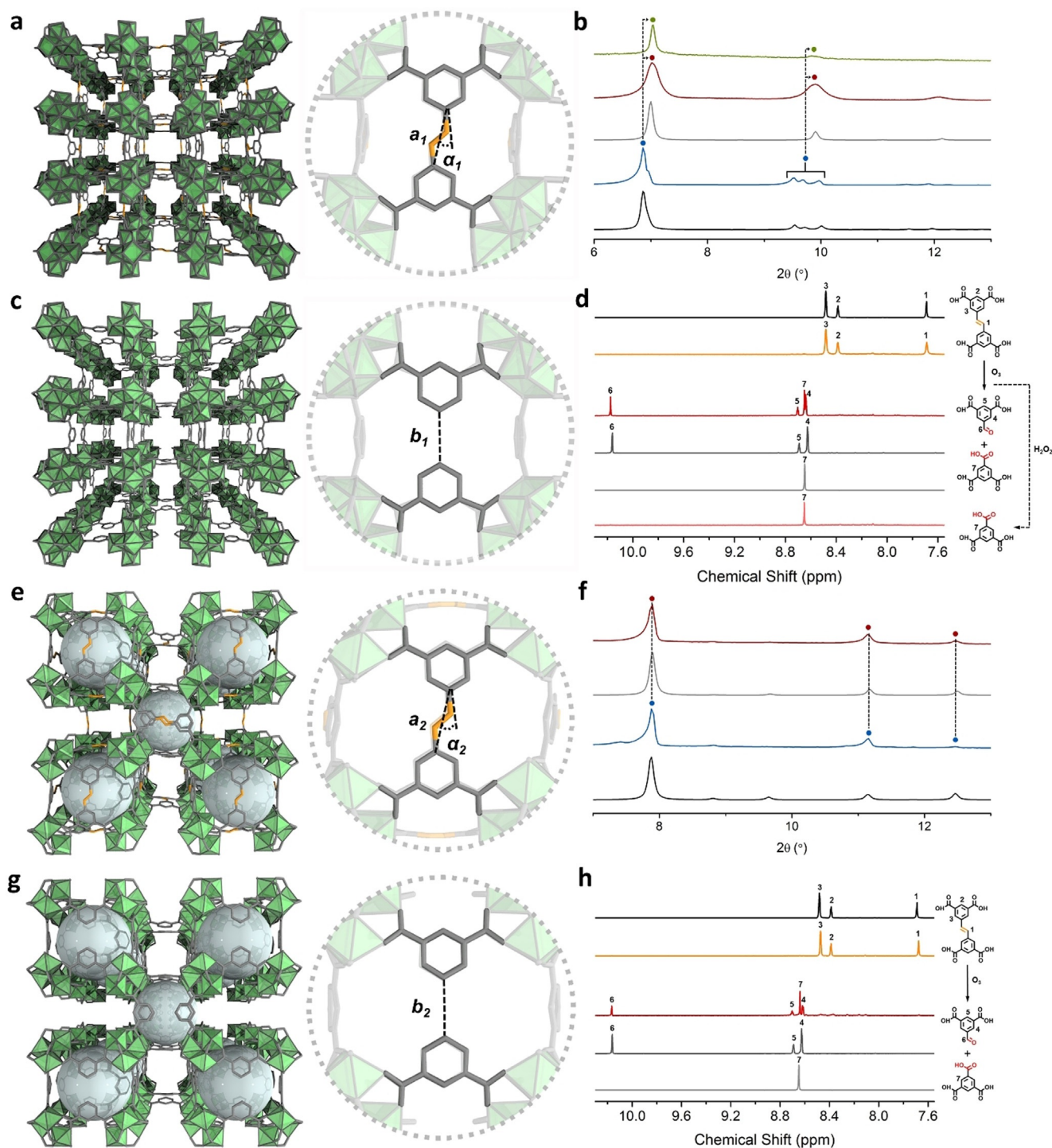


Figure 2. Structural and molecular characterization of Zr-*pcu*-MOF and Sc-*pcu*-MOF. a,c) Crystal structures of isorecticular Zr-*scu*-MOF (a) and Zr-*pcu*-MOF (c). Magnified views highlight the changes observed in the distances and angles of both phenyl rings (from $a_1 = 3.77\text{--}3.79\text{ \AA}$ and $\alpha_1 = 14.95\text{--}19.71^\circ$ to $b_1 = 3.39\text{--}3.65\text{ \AA}$ and $\beta_1 = 0^\circ$) initially composing L_2 .^[41] b) Magnified view of XRPD spectra for calculated Zr-*scu*-MOF (black), synthesized Zr-*scu*-MOF (blue), calculated Zr-*pcu*-MOF (grey), synthesized Zr-*pcu*-MOF (red) and oxidized Zr-*pcu*-MOF (green). The main structural changes with signal shifts are highlighted. d) ^1H NMR spectra (360 MHz, $[\text{D}_6]\text{DMSO}$) of digested L_2 (black), Zr-*scu*-MOF (orange), Zr-*pcu*-MOF (red), 5-formylisophthalic acid (dark grey), trimesic acid (light grey) and oxidized Zr-*pcu*-MOF (light grey). Assigned proton signals: $\delta_1 = 7.69\text{ ppm}$ (s, 2H), $\delta_2 = 8.39\text{ ppm}$ (s, 2H), $\delta_3 = 8.49\text{ ppm}$ (s, 4H), $\delta_4 = 8.64\text{ ppm}$ (m, 2H), $\delta_5 = 8.70\text{ ppm}$ (m, 1H), $\delta_6 = 10.18\text{ ppm}$ (s, 1H) and $\delta_7 = 8.65\text{ ppm}$ (s, 3H). e,g) Crystal structures of isorecticular Sc-*soc*-MOF (e) and Sc-*pcu*-MOF (g). Magnified views highlight the changes observed in the distances and angles in both phenyl rings (from $a_2 = 3.82\text{--}3.84\text{ \AA}$ and $\alpha_2 = 15.63\text{--}17.34^\circ$ to $b_2 = 3.62\text{--}3.63\text{ \AA}$ and $\beta_2 = 0^\circ$) initially composing L_2 .^[41] f) Magnified view of the XRPD spectra for calculated Sc-*soc*-MOF (black), synthesized Sc-*soc*-MOF (blue), calculated Sc-*pcu*-MOF (grey) and synthesized Sc-*pcu*-MOF (red). h) ^1H NMR spectra (360 MHz, $[\text{D}_6]\text{DMSO}$) of digested L_2 (black), Sc-*soc*-MOF (orange), Sc-*pcu*-MOF (red), 5-formylisophthalic acid (dark grey) and trimesic acid (light grey). Assigned proton signals: $\delta_1 = 7.68\text{ ppm}$ (s, 2H), $\delta_2 = 8.38\text{ ppm}$ (s, 2H), $\delta_3 = 8.47\text{ ppm}$ (s, 4H), $\delta_4 = 8.64\text{ ppm}$ (m, 2H), $\delta_5 = 8.71\text{ ppm}$ (m, 1H), $\delta_6 = 10.17\text{ ppm}$ (s, 1H) and $\delta_7 = 8.65\text{ ppm}$ (s, 3H).

in Zr-**scu**-MOF was different after ozonolysis (Figures 2a,c), indicating that the olefin bond was no longer present to fix the angle between these rings.

Since the crystal structure of pristine Zr-**scu**-MOF differed markedly to that of ozonated Zr-**scu**-MOF (or Zr-**pcu**-MOF), we also studied these MOFs by XRPD. Remarkably, the XRPD patterns for each sample perfectly matched those calculated from the corresponding structures determined by SCXRD and full-pattern profile refinements further demonstrated phase purity of the samples (Figures 2b, S3–S5). Altogether, these results corroborate two crucial phenomena for validation of Clip-off Chemistry: firstly, that it is indeed possible to cleave all the periodic olefinic bonds in a 3D structure without destroying it or its single-crystal character; and secondly, that said cleavage, and the resultant formation of a new structure (in this case, Zr-**pcu**-MOF),^[19] are homogeneous throughout the bulk crystalline sample.

Next, we gained further evidence of the formation of Zr-**pcu**-MOF by recording the ¹H NMR spectra of the digested ozonated samples (5% HF/[D₆]DMSO) after each cycle, and then comparing each spectrum to that of the starting Zr-**scu**-MOF (Figures 2d, S6–S8). Under these digestion conditions, the MOF structures are destroyed and the linkers, released, thus enabling use of ¹H NMR to unveil the composition of the initial MOF structures. The spectrum of the digested Zr-**scu**-MOF showed the characteristic peak of equivalent olefinic protons of L₂ at $\delta = 7.69$ ppm. In contrast, the spectra of ozonated crystals after each cycle confirmed a gradual fading of this olefinic signal, which, by the ninth cycle, had fully disappeared. Indeed, ¹H NMR of digested ozonated Zr-**scu**-MOF after the ninth cycle confirmed the full conversion of L₂ into doubly deprotonated trimesic acid and 5-formylisophthalate. Beyond the disappearance of the olefinic protons at $\delta = 7.69$ ppm, there was also fading of the phenyl ($\delta = 8.49$ ppm and 8.39 ppm) and the carboxylic acid ($\delta = 13.32$ ppm) protons of L₂, whereas the characteristic signals for the trimesic acid ($\delta = 13.57$ ppm and 8.65 ppm) and 5-formylisophthalic acid ($\delta = 10.18$ ppm, 8.70 ppm and 8.64 ppm) were clearly identifiable. Cleavage of the olefinic bonds was corroborated by negative-mode mass spectrometry and Fourier transform infrared (FT-IR) spectroscopy of both pristine and ozonated Zr-MOFs (Table S3, Figures S10, S11). In the mass spectrum, the molecular ions $[M-H]^-$ corresponding to trimesic acid ($m/z = 209.01$) and 5-formylisophthalic acid ($m/z = 193.01$) were found, in strong contrast to the absence of any molecular ion $[M-H]^-$ corresponding to L₂ ($m/z = 355.05$). Similarly, in comparison to the spectrum of pristine Zr-**scu**-MOF, the FT-IR spectrum of ozonated Zr-**pcu**-MOF revealed the appearance of a typical carbonyl (C=O) stretching band at 1700 cm^{-1} and the complete disappearance of an alkene (C=C) stretching band at 1622 cm^{-1} .

Having demonstrated the single-crystal-to-single-crystal synthesis of Zr-**pcu**-MOF by selectively cleaving the olefinic bonds in Zr-**scu**-MOF into a mixture of aldehyde and carboxylic acid groups, we next sought to perform analogous chemistry to synthesize Zr-**pcu**-MOF functionalized exclusively with carboxylic acids to show enhanced control over the final output of the Clip-off Chemistry. To this end, ozonated crystals were soaked in 1 mL of hydrogen peroxide (30 wt. %

in H₂O) solution for 3 weeks. During this period, the sample was refreshed with fresh hydrogen peroxide every 24 h. Next, the sample was centrifuged, and then washed twice with water. The transformation to carboxylic acid groups was quantitative, as confirmed by ¹H NMR (Figures 2d, S9). Moreover, the Zr-**pcu**-MOF framework had been preserved, as confirmed by XRPD (Figures 2b, S3).

To show that we could generalize Clip-off Chemistry to other 3D MOF structures, we next attempted to synthesize a 3D Sc-**pcu**-MOF from an Sc-**soc**-MOF precursor (Figure 1; see SI, section 3),^[31] a 3D structure built up from linking 6-c trigonal, prismatic Sc₃O clusters to 4-c L₁ linkers in a 4,6-c **soc/edq** topology.^[32] This structure exhibits a mixture of cubic cavities (size: 11 Å) and 1D channels (size: 8 Å) along the three axes. As in the previous case, we designed the precursor by replacing L₁ with L₂, thus forming an isorecticular Sc-**soc**-MOF that contains different circuits of connections, some of which contains the cleavable olefins. We envisioned that, upon treatment with ozone, this circuit would be disrupted to form a 3D Sc-**pcu**-MOF whose Sc₃O clusters would be connected through trimesate/5-formylisophthalate linkers.

We began the clip-off synthesis of Sc-**pcu**-MOF via the aforementioned route by first preparing the isorecticular Sc-**soc**-MOF precursor. Colorless cubic crystals of Sc-**soc**-MOF were prepared by heating a solution of Sc(NO₃)₃·xH₂O and L₂ in DMF, ethanol and formic acid at 120°C for 48 h (Figure 2e). However, all attempts at complete ozonolysis were unsuccessful, whether using the same synthetic protocol as for Zr-**scu**-MOF or trying slight modifications (e.g. extending the reaction time up to 8 h and/or the number of ozonolysis cycles up to twelve; Figures S13–S16). Consequently, cleavage of the olefinic bonds was incomplete, reaching a maximum value of 60% to 70% under certain conditions (e.g. exposing the Sc-**soc**-MOF crystals to ozone gas for 2 h). Consequently, a distinct ozonolysis protocol was employed: Sc-**soc**-MOF crystals were immersed in water, and then ozone was bubbled through the suspension under stirring at room temperature for 12 h. These conditions afforded greater cleavage of the olefinic bonds than in the previous strategy, leading to a mixture of trimesic acid, 5-formylisophthalic acid and the intermediate 1,2,4-trioxolane ring (Figure S17). Importantly, the presence of this intermediate indicated that the olefinic bonds had not all been completely cleaved to aldehyde/carboxylic acid groups. Moreover, increasing the reaction time under these solid/liquid conditions did not provide any major improvement in cleavage, although it did lead to a slight decrease in the crystallinity of the ozonated Sc-**pcu**-MOF.

To address the above drawbacks, we decided to combine the two ozonolysis strategies by first running a solid-gas reaction for 2 h and then, cleaving the remaining alkene bonds via suspension/gas reaction for an additional 6 h. Under these conditions, SCXRD of the resulting crystals confirmed quantitative single-crystal-to-single-crystal cleavage of the olefinic bonds of Sc-**soc**-MOF to synthesize Sc-**pcu**-MOF (Figure 2g, S19, S26).^[19] However, in this case, no changes were observed in the volume of the R-3 rhombohedral unit cell relative to that of the precursor, as also confirmed by XRPD (Figures 2f, S20). Nevertheless, SCXRD analysis

showed a very similar case to that of ozonated Zr-**scu**-MOF. Thus, the connectivity of the atoms belonging to the inorganic trimeric ScO_3 clusters remained identical to that of the pristine Sc-**soc**-MOF. Refinement of the carbon atoms from the organic linkers evidenced a positional disorder for some of them, and, unlike Sc-**soc**-MOF, the Sc-**pcu**-MOF product did not contain any olefinic atoms. Instead, areas of electron density were observed only between the opposite phenyl rings, with a maximum value at the middle point between the two rings, but at a distance longer than that expected for a C=C bond. This area of higher electron-density points perpendicularly above and below the plane of the phenyl rings. Although the refinement indicates the presence of atoms in this area, these atoms could not be unambiguously assigned to aldehyde or carboxylate groups (Figure S18). These findings indicate that the functional groups are not arranged in an orderly fashion within the crystals after ozonolysis but are

instead randomly oriented in the pores. This is not surprising, considering that the resulting aldehydes and/or carboxylic groups are randomly distributed and most likely dangle in different orientations into the pores, rather than having a periodically fixed position, such that they would not contribute to the periodic diffraction of the crystal. Consistent with these SCXRD data, cleavage of all olefinic bonds was confirmed by ^1H NMR (Figures 2h, S21–S23) and negative-mode mass spectrometry of the digested ozonated samples (5% HF/[D_6]DMSO) (Figure S24, Table S6), and FT-IR of ozonated Sc-**pcu**-MOF (Figure S25), from which the olefinic protons ($\delta = 7.68$ ppm), molecular ion $[\text{M}-\text{H}]^-$ of L_2 and the typical alkene (C=C) stretching band, respectively, were not observed. On the contrary, the ^1H NMR signals, the molecular ions $[\text{M}-\text{H}]^-$ and the carbonyl (C=O) stretching band corresponding to doubly deprotonated trimesic acid and 5-

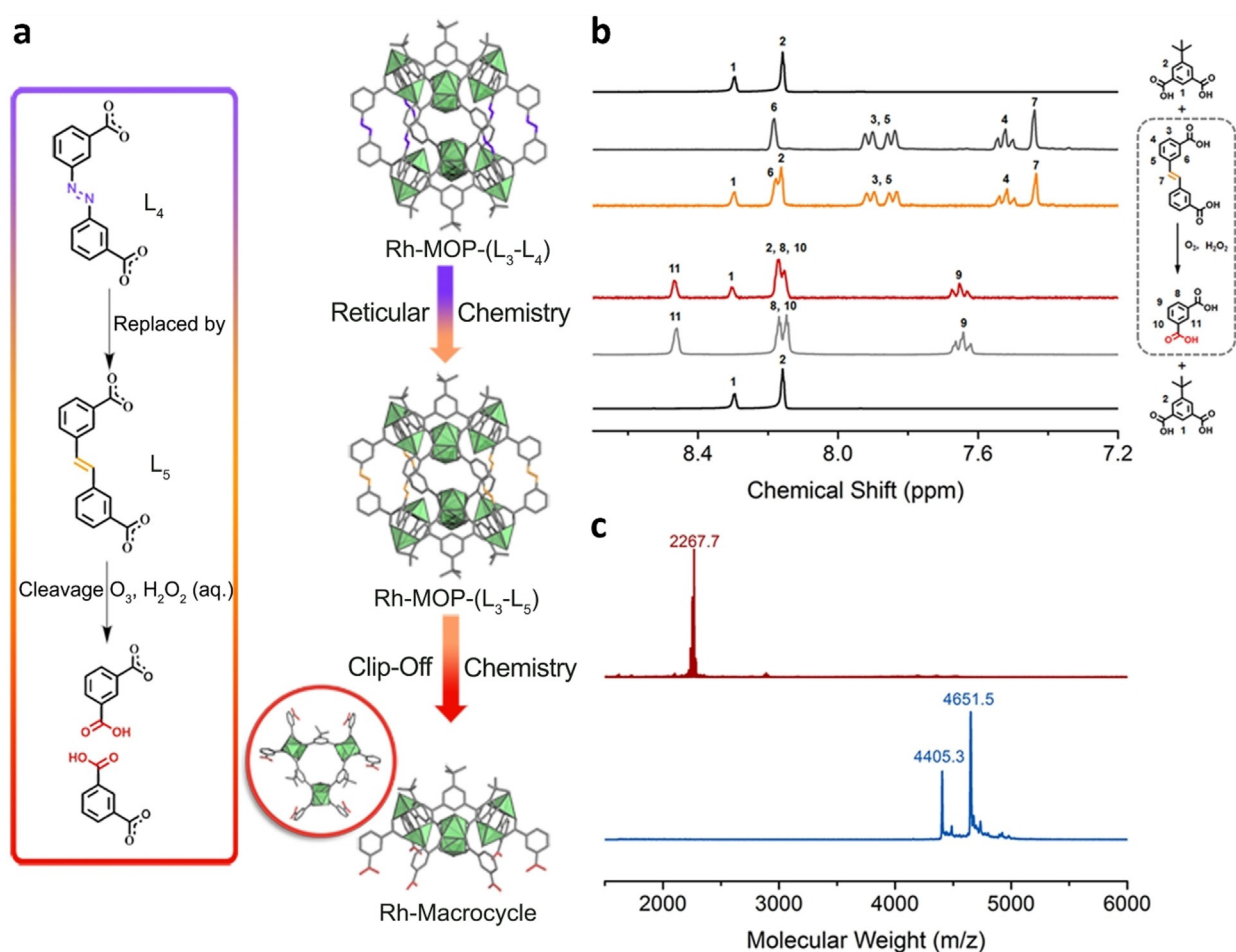


Figure 3. Clip-off synthesis of a triangular Rh-macrocycle. a) Schematic representation of the synthesis of a Rh-macrocycle from a discrete mixed-linker Rh-MOP, in which a linker containing an olefinic bond had been incorporated by reticular chemistry previous to ozonolysis.^[41] b) ^1H NMR spectra (360 MHz, [D_6]DMSO) of digested Rh-MOP (black), L_5 (dark grey), Rh-MOP (orange), Rh-macrocycle (red), and isophthalic acid (light grey). Assigned proton signals for digested Rh-MOP (orange): $\delta_1 = 8.30$ ppm (s, 1H), $\delta_2 = 8.16$ ppm (s, 2H), $\delta_{3,5} = 7.92$ ppm (d, $J = 7.7$ Hz, 2H), $\delta_{3,5} = 7.85$ ppm (d, $J = 7.7$ Hz, 2H), $\delta_4 = 7.51$ ppm (t, $J = 7.7$ Hz, 2H), $\delta_6 = 8.18$ ppm (s, 2H), and $\delta_7 = 7.43$ ppm (s, 2H). Assigned proton signals for digested Rh-macrocycle (red): $\delta_1 = 8.30$ ppm (s, 1H), $\delta_{2,8,10} = 8.17$ – 8.15 ppm (m, 6H), $\delta_9 = 7.65$ ppm (t, $J = 7.8$ Hz, 2H), and $\delta_{11} = 8.47$ ppm (s, 2H). c) MALDI-TOF spectra of Rh-MOP (blue) and of Rh-macrocycle fully functionalized with $-\text{COOH}$ (red). The mass corresponding to the formula $[\text{Rh}_{12}(\text{L}_3)_6(\text{L}_5)_6(\text{DMA})_2(\text{H}_2\text{O})_2(\text{MeOH})_4 + \text{H}]^+$ (expected = 4403.8; found = 4405.3) and $[\text{Rh}_{12}(\text{L}_3)_6(\text{L}_5)_6(\text{H}_2\text{O})_2(\text{DMA})_2(\text{CH}_3\text{CN})_7 + \text{H}]^+$ (expected = 4650.0; found = 4651.5) have been highlighted for the Rh-MOP sample. In the case of the Rh-macrocycle, the mass corresponding to the formula $[\text{Rh}_6(\text{L}_3)_3(\text{C}_8\text{H}_5\text{O}_4)_6 + \text{H}]^+$ has been highlighted (expected = 2268.8; found = 2267.7).

formylisophthalate were all clearly identifiable, thus further corroborating the clip-off synthesis of Sc-**pcu**-MOF.

Finally, we endeavoured to use Clip-off Chemistry to synthesize a metal-organic macrocycle^[33–36] from a 0-D MOP system. To this end, we followed the second approach mentioned above, by designing a mixed-linker Rh-MOP that we could transform into a triangular metal-organic macrocycle (Figure 3a, S27–S34). We selected a Rh-MOP^[37] built from six 4-c Rh paddle-wheel clusters linked by six 5-*tert*-butylbenzene-1,3-dicarboxylate (L_3) linkers and by six 3-[(3-carboxyphenyl)diazanyl]benzoate (L_4) linkers that together form a cage (diameter: 12 Å). In this cage, three paddle-wheel clusters are linked by three L_3 linkers to form a triangular macrocycle, and two of these units are linked by six L_4 linkers. Following a similar strategy as those explained in the previous examples, we functionalized this MOP with alkene groups by replacing L_4 with 3-[2-(3-carboxyphenyl)ethenyl]benzoate (L_5). We reasoned that the isoreticular Rh-MOP would contain a non-cleavable L_3 linker and a cleavable L_5 linker, which, upon cleavage via ozonolysis, would split the Rh-MOP into two equal fragments. We hypothesized that this splitting would release the metal-organic macrocycle built up from the three 4-c Rh^{II} paddle-wheel units linked to each other by the three L_3 linkers and with six pendant partly deprotonated isophthalic linkers.

We synthesized isoreticular Rh-MOP by heating a suspension of L_3 , L_5 , Na_2CO_3 and $\text{Rh}_2(\text{OAc})_4$ in *N,N*-dimethylacetamide (DMA) at 100 °C. After 4 days, the reaction yielded a dark precipitate that was centrifuged to separate out the Na_2CO_3 . The resultant solution was precipitated in MeOH to yield a green powder, which was washed several times with MeOH. Finally, diffusion of diethyl ether into a solution of this green powder in DMF afforded green parallelogram-shaped crystals of Rh-MOP. SCXRD confirmed the formation of the expected isoreticular MOP, built up from six L_3 linkers and six cleavable L_5 linkers (Figure 3a). Next, the six linkers were cleaved to synthesize the metal-organic macrocycle by bubbling ozone through a suspension of Rh-MOP in DMA and hydrogen peroxide (50% wt. in H_2O) at room temperature for 30 min. Note that oxidative conditions were used in this clip-off reaction to obtain a pure Rh-macrocycle functionalized with six carboxylic acid groups. Afterwards, the resulting green suspension was centrifuged, and an aqueous HCl solution was added to the supernatant to precipitate out the Rh-macrocycle as a green solid. This solid was finally separated by centrifugation, washed with water three times, and dried at 85 °C under vacuum.

We confirmed formation of the expected metal-organic Rh-macrocycle by ^1H NMR of the digested ozonated Rh-MOP (5% HF/ $[\text{D}_6]$ DMSO; Figure 3b), MALDI-TOF mass (Figure 3c) spectrometry and UV/Vis spectroscopy (Figure S33). The ^1H NMR spectrum lacked all the characteristic peaks of L_5 (olefinic protons at $\delta = 7.43$ ppm; and phenyl protons at $\delta = 8.18$ ppm, 7.92 ppm, 7.85 ppm and 7.51 ppm), yet it did reveal the characteristic signals of L_3 (phenyl protons at $\delta = 8.30$ ppm and 8.16 ppm; and *tert*-butyl protons at $\delta = 1.33$ ppm) and those of isophthalic acid (phenyl protons at $\delta = 8.47$ ppm, 8.17 ppm and 7.65 ppm; Figure 3b). This integrated spectrum indicated an L_3 /isophthalic acid proton

ratio of 1:2, consistent with the formula expected for the Rh-macrocycle (Figures S31, S32). Moreover, the absence of any proton signal corresponding to 3-formylbenzoic acid corroborated full cleavage of all the olefinic bonds in the Rh-MOP and their subsequent transformation to carboxylic acid groups.

Finally, we unambiguously confirmed the structure of the targeted macrocycle by positive-mode MALDI-TOF on pristine and ozonated samples of the Rh-MOP. The MALDI-TOF spectrum of the Rh-MOP showed its molecular ion $[M+\text{H}]^+$ ($m/z = 4651.5$), whereas that of the ozonated Rh-MOP did not, but did contain a new peak, for the molecular ion $[M+\text{H}]^+$ ($m/z = 2267.7$) corresponding to the Rh-macrocycle (Figure 3c). Moreover, UV/Vis analysis of both pristine and ozonated Rh-MOP samples did not reveal any shift in the low-energy absorption band I (λ_{max}) at 592 nm, indicating that the coordination of Rh^{II} ions in the ozonated solid had not changed, thus further corroborating formation of the desired Rh-macrocycle (Figure S33).

Conclusion

We have introduced Clip-off Chemistry, a new approach to synthesizing molecules and materials based on selective bond-breaking in reticular precursors materials via common organic transformations, via programmed de-reticulation and controlled etching at the molecular level. As proof-of-concept, we transformed two 3D MOFs (Zr-**scu**-MOF and Sc-**soc**-MOF) into two topologically distinct 3D MOFs (Zr-**pcu**-MOF and Sc-**pcu**-MOF, respectively). Moreover, we extended Clip-off Chemistry to a 0-D system, by transforming a MOP into a metal-organic macrocycle. In the examples that we have reported here, we demonstrated that the cleavage was quantitative and selective; was effective both in solid-phase and solution-phase chemistry; and occurred in a single-crystal-to-single crystal fashion across the entire bulk precursor sample. Moreover, we demonstrated control over the cleavage of each olefinic bond into carboxylic acid groups using oxidative conditions.

Our preliminary results suggest that Clip-off Chemistry is ripe for further exploration. Since it is based on bond cleavage, the dimensionality of the parent reticular material dictates the synthetic feasibility of the target molecules and/or materials (Figure 4). Thus, it offers the possibility to modify structures of reticular materials without changing their dimensionality (e.g. 3D \rightarrow 3D, or 2D \rightarrow 2D). For example, one might employ Clip-off Chemistry for post-synthetic modification of the topology and/or the porosity of a given material. Moreover, it could be applied to 3D structures to augment the diversity of new 2D materials: for instance, by converting well-known 3D pillared reticular materials into isolated 2D layers, via selective clipping of the pillaring linkers. Similarly, it shows promise for using 3D or 2D structures to isolate 1D materials in the form of metallic chains, or to synthesize 0-D systems, including MOPs, macrocycles and clusters, from 3D/2D/1D structures and even from other 0-D systems (e.g. MOPs). Cleavage of bonds in reticular materials may also be expanded to purely organic structures.

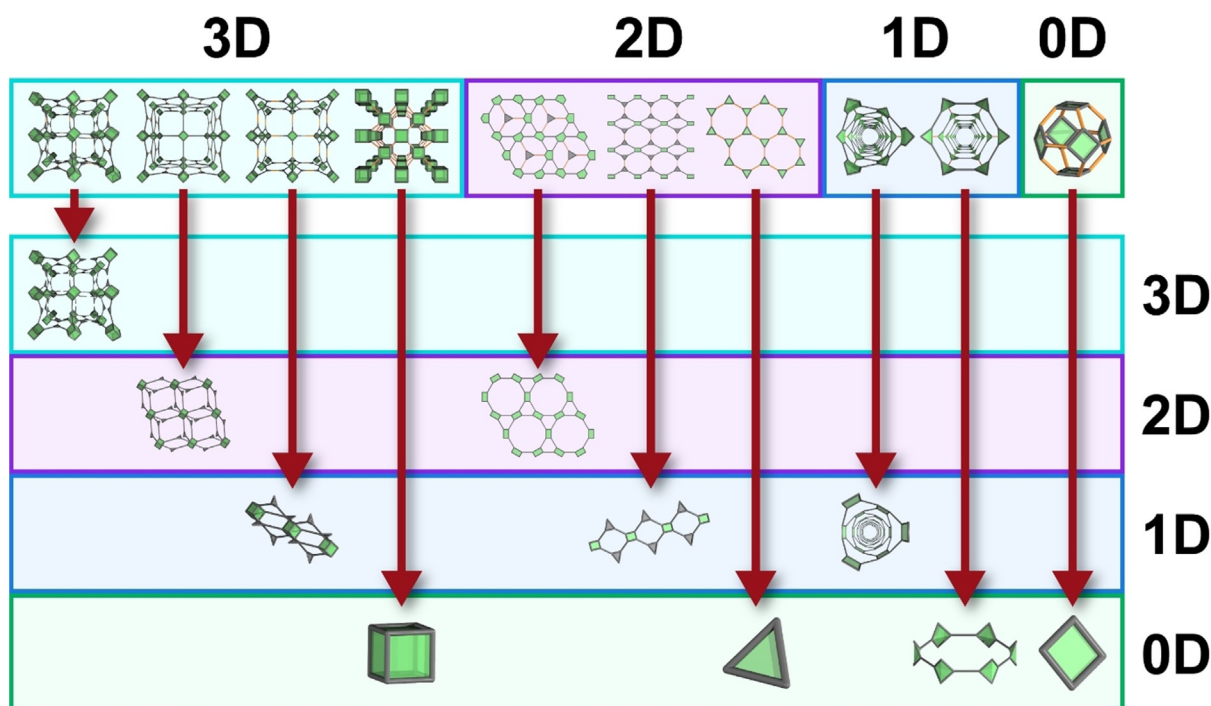


Figure 4. Clip-off Chemistry for the synthesis of molecular architectures of different dimensionality. Schematic illustrating the potential outcomes of Clip-off Chemistry, in which the dimensionality of the parent reticular materials dictates the dimensionality of the target molecules and structures.

Indeed, COFs and organic cages are another endless source of precursors in Clip-off Chemistry for possible synthesis of organic polymers, cages, macrocycles or other organic compounds. Similarly, other reactions involving the cleavage of bonds (e.g. photolysis) are potential candidates to be applied in reticular materials for their programmable disassembly.^[38–40] In summary, our results prove that the programmed disassembly of reticular materials is feasible, and that Clip-off Chemistry could provide researchers with access to myriad new molecular architectures.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: bond breaking · disassembly · metal-organic frameworks · metal-organic polyhedra · reticular materials

- [1] H. Li, M. Eddaoudi, T. L. Groy, O. M. Yaghi, *J. Am. Chem. Soc.* **1998**, *120*, 8571–8572.
- [2] O. M. Yaghi, M. O'Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi, J. Kim, *Nature* **2003**, *423*, 705–714.
- [3] H. Li, M. Eddaoudi, M. O'Keeffe, O. M. Yaghi, *Nature* **1999**, *402*, 276–279.
- [4] O. M. Yaghi, G. Li, H. Li, *Nature* **1995**, *378*, 703–706.
- [5] S. Kitagawa, R. Kitaura, S. I. Noro, *Angew. Chem. Int. Ed.* **2004**, *43*, 2334–2375; *Angew. Chem.* **2004**, *116*, 2388–2430.
- [6] B. F. Abrahams, B. F. Hoskins, D. M. Michail, R. Robson, *Nature* **1994**, *369*, 727–729.
- [7] B. F. Hoskins, R. Robson, *J. Am. Chem. Soc.* **1989**, *111*, 5962–5964.
- [8] O. M. Yaghi, M. J. Kalmutzki, C. S. Diercks, *Introduction to Reticular Chemistry: Metal-Organic Frameworks and Covalent Organic Frameworks*, Wiley-VCH, Weinheim, **2019**.
- [9] X. Feng, X. Ding, D. Jiang, *Chem. Soc. Rev.* **2012**, *41*, 6010–6022.
- [10] D. J. Tranchemontagne, Z. Ni, M. O'Keeffe, O. M. Yaghi, *Angew. Chem. Int. Ed.* **2008**, *47*, 5136–5147; *Angew. Chem.* **2008**, *120*, 5214–5225.
- [11] J. J. Perry IV, J. A. Perman, M. J. Zaworotko, *Chem. Soc. Rev.* **2009**, *38*, 1400–1417.
- [12] S. Lee, H. Jeong, D. Nam, M. S. Lah, W. Choe, *Chem. Soc. Rev.* **2021**, *50*, 528–555.

- [13] M. Eddaoudi, D. B. Moler, H. Li, B. Chen, T. M. Reineke, M. O'Keeffe, O. M. Yaghi, *Acc. Chem. Res.* **2001**, *34*, 319–330.
- [14] M. Eddaoudi, J. Kim, N. Rosi, D. Vodak, J. Wachter, M. O'Keeffe, O. M. Yaghi, *Science* **2002**, *295*, 469–472.
- [15] S. M. Cohen, *Chem. Rev.* **2012**, *112*, 970–1000.
- [16] O. M. Yaghi, *Mol. Front. J.* **2019**, *3*, 66–83.
- [17] M. O'Keeffe, O. M. Yaghi, *Chem. Rev.* **2012**, *112*, 675–702.
- [18] M. O'Keeffe, M. A. Peskov, S. J. Ramsden, O. M. Yaghi, *Acc. Chem. Res.* **2008**, *41*, 1782–1789.
- [19] V. A. Blatov, A. P. Shevchenko, D. M. Proserpio, *Cryst. Growth Des.* **2014**, *14*, 3576–3586.
- [20] A. F. Wells, *Three-Dimensional Nets and Polyhedral*, Wiley, Hoboken, **1977**.
- [21] H. Wang, X. Dong, J. Lin, S. J. Teat, S. Jensen, J. Cure, E. V. Alexandrov, Q. Xia, K. Tan, Q. Wang, D. H. Olson, D. M. Proserpio, Y. J. Chabal, T. Thonhauser, J. Sun, Y. Han, J. Li, *Nat. Commun.* **2018**, *9*, 1745.
- [22] M. Li, D. Li, M. O'Keeffe, O. M. Yaghi, *Chem. Rev.* **2014**, *114*, 1343–1370.
- [23] J. Albalad, H. Xu, F. Gándara, M. Haouas, C. Martineau-Corcós, R. Mas-Ballesté, S. A. Barnett, J. Juanhuix, I. Imaz, D. Maspoch, *J. Am. Chem. Soc.* **2018**, *140*, 2028–2031.
- [24] V. Guillermin, H. Xu, J. Albalad, I. Imaz, D. Maspoch, *J. Am. Chem. Soc.* **2018**, *140*, 15022–15030.
- [25] R. Criegee, *Angew. Chem. Int. Ed. Engl.* **1975**, *14*, 745–752; *Angew. Chem.* **1975**, *87*, 765–771.
- [26] C. E. Schiaffo, P. H. Dussault, *J. Org. Chem.* **2008**, *73*, 4688–4690.
- [27] L. B. Harding, W. A. Goddard III, *J. Am. Chem. Soc.* **1978**, *100*, 7180–7188.
- [28] L. H. Xie, X. M. Liu, T. He, J. R. Li, *Chem* **2018**, *4*, 1911–1927.
- [29] S. Wang, L. Chen, M. Wahiduzzaman, A. Tissot, L. Zhou, I. A. Ibarra, A. Gutiérrez-Alejandre, J. S. Lee, J. S. Chang, Z. Liu, J. Marrot, W. Shepard, G. Maurin, Q. Xu, C. Serre, *Matter* **2021**, *4*, 182–194.
- [30] H. Furukawa, F. Gándara, Y. B. Zhang, J. Jiang, W. L. Queen, M. R. Hudson, O. M. Yaghi, *J. Am. Chem. Soc.* **2014**, *136*, 4369–4381.
- [31] J. W. Zhang, P. Qu, M. C. Hu, S. N. Li, Y. C. Jiang, Q. G. Zhai, *Inorg. Chem.* **2019**, *58*, 16792–16799.
- [32] Y. Liu, J. F. Eubank, A. J. Cairns, J. Eckert, V. C. Kravtsov, R. Luebke, M. Eddaoudi, *Angew. Chem. Int. Ed.* **2007**, *46*, 3278–3283; *Angew. Chem.* **2007**, *119*, 3342–3347.
- [33] P. J. Stang, B. Olenyuk, *Acc. Chem. Res.* **1997**, *30*, 502–518.
- [34] B. Olenyuk, A. Fechtenkötter, P. J. Stang, *J. Chem. Soc. Dalton Trans.* **1998**, 1707–1728.
- [35] M. Fujita, O. Sasaki, T. Mitsunishi, T. Fujita, J. Yazaki, K. Yamaguchi, K. Ogura, *Chem. Commun.* **1996**, 1535–1536.
- [36] F. A. Cotton, L. M. Daniels, C. Lin, C. A. Murillo, *J. Am. Chem. Soc.* **1999**, *121*, 4538–4539.
- [37] J. R. Li, H. C. Zhou, *Nat. Chem.* **2010**, *2*, 893–898.
- [38] L. Feng, K. Y. Wang, G. S. Day, M. R. Ryder, H. C. Zhou, *Chem. Rev.* **2020**, *120*, 13087–13133.
- [39] K. Y. Wang, L. Feng, T. H. Yan, S. Wu, E. A. Joseph, H. C. Zhou, *Angew. Chem. Int. Ed.* **2020**, *59*, 11349–11354; *Angew. Chem.* **2020**, *132*, 11445–11450.
- [40] P. Shieh, M. R. Hill, W. Zhang, S. L. Kristufek, J. A. Johnson, *Chem. Rev.* **2021**, *121*, 7059–7121.
- [41] Deposition Numbers 2080949 (for Zr-*scu*-MOF), 2080950 (for Zr-*pcu*-MOF), 2080951 (for Sc-*soc*-MOF), 2080952 (for Sc-*pcu*-MOF) and 2080953 (for Rh-MOP) contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service www.ccdc.cam.ac.uk/structures.

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