The mobility of the cap domain is essential for the substrate promiscuity of a family IV esterase from sorghum rhizosphere microbiome

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Running title: The cap domain of an esterase from sorghum rhizosphere

ABSTRACT Metagenomics offers the possibility to screen for versatile biocatalysts. In this study, the microbial community of the *Sorghum bicolor* rhizosphere was spiked with technical cashew nut shell liquid, and after incubation, the eDNA was extracted and subsequently used to build a metagenomic library. We report the biochemical features and crystal structure of a novel esterase from the family IV, EH_0, retrieved from an uncultured sphingomonad after a functional screen in tributyrin agar plates. EH_0 (T_{opt}, 50 °C; T_m, 55.7 °C; pH_{opt}, 9.5) was stable in the presence of 10-20% v/v organic solvents and exhibited hydrolytic activity against *p*-nitrophenyl esters from acetate to palmitate, preferably butyrate (496 U mg^{-1}), and a large battery of 69 structurally different esters (up to 30.2 U mg^{-1}), including bis(2-hydroxyethyl)-terephthalate (0.16 ± 0.06 U mg^{-1}). This broad substrate specificity contrasts with the fact that EH_0 showed a long and narrow catalytic tunnel, whose access appears to be hindered by a thigth folding of its cap domain. We propose that this cap domain is a highly flexible structure whose opening is mediated by unique structural elements, one of which is the presence of two contiguous proline residues likely acting as possible hinges, that altogether allow for the entrance of the substrates. Therefore, this work provides a new role for the cap domain, which until now was thought to be immobile elements that contain hydrophobic patches involved in substrate pre-recognition and in turn substrate specificity within family IV esterases.

IMPORTANCE A better understanding of structure–function relationships of enzymes allows revealing key structural motifs or elements. Here, we studied the structural basis of the substrate promiscuity of EH_0, a family IV esterase, isolated from a sample of the *Sorghum bicolor* rhizosphere microbiome exposed to technical cashew nut shell liquid. The analysis of EH_0 revealed the potential of the sorghum rhizosphere microbiome as a source of enzymes

with interesting properties, such as pH and solvent tolerance and remarkably broad substrate promiscuity. Its structure resembled those of homologous proteins from mesophilic *Parvibaculum* and *Erythrobacter* spp. and hyperthermophilic *Pyrobaculum* and *Sulfolobus* spp. and had a very narrow, single-entry access tunnel to the active site, access which is controlled by a capping domain that includes a number of not conserved proline residues. These structural markers, distinct from those of other substrate promiscuous esterases, can help tuning substrate profiles beyond tunnel and active site engineering.

KEYWORDS Crystal structure, esterase, α/β-fold hydrolase, metagenome, promiscuity, rhizosphere.

Currently, in the biotech industrial sector, there is a constant demand for novel biocatalysts with enhanced biochemical properties fulfilling industrial requirements to replace low-performance enzymes and dismiss chemical processes (1). From this perspective, the enzymatic diversity within the microbial communities, that may reach for example up to 10^3-10^5 microbial species in 1 g of soil, represents a yet unexplored and exceptional resource for new biocatalysts (2, 3), and thus, it can be a source of biocatalysts. A straightforward evaluation of such diversity can be performed by metagenomics, through a number of bioinformatics and so-called naïve screening methods (2, 4-6).

Carboxylic ester hydrolases (EC 3.1.1.-) are a class of enzymes widely distributed in nature that have attracted much attention because of their high sequence diversity, structural versatility, catalytic versatility, robustness and lack of need for cofactors (7-10). Considering the importance of these classes of enzymes, it is not surprising that they are priority targets to screen by metagenomics. For example, approximately 280,638 sequences encoding

71 carboxylic ester hydrolases have been cataloged (10), and more than 4,000 new enzymes
72 have been discovered through metagenomics (11); few of them show enhanced biophysical
73 properties, such as stability at extreme temperatures, salinity, pH and solvents conditions,
74 high catalytic efficiency, broad substrate specificity and regio- and enantioselectivity (6, 12-
75 14). Additionally, metagenomic studies on soil environments significantly contributed to
76 broadening the knowledge about this class of enzymes with the reannotation of sequences
77 known as hypothetical proteins and the definition of new esterase families (15, 16).
78 Carboxylic ester hydrolases are also the most studied enzymes with respect to promiscuity
79 (17), including catalytic (18) and substrate (19) promiscuity. The question that arises is, would
80 it not be more efficient to have just a couple of promiscuous enzymes with the ability to
81 perform a wide range of reactions (19). Based on this principle, biotechnological industries
82 demand biocatalysts that are capable of transforming a wide range of substrates. Their
83 isolation has been solved through the application of metagenomic techniques that have
84 emerged as robust tools for the discovery of unknown biocatalysts, including ester hydrolases
85 with a broad substrate scope. This method, together with the understanding of the structural
86 mechanisms and engineering behind promiscuous enzymes, seems crucial for their industrial
87 implementation. In this context, our recent study of approximately 145 ester hydrolases has
88 revealed that members of family IV show higher levels of substrate promiscuity than those of
89 other families. This is the result of their capacity to adapt the topology of the large but
90 occluded active sites to a high variety of substrates but also to the presence of a cap domain
91 next to the entrance of the substrate tunnel (19). The cap domains were thought to be
92 immobile elements, unlike lid elements in lipases, that contain hydrophobic patches involved
93 in substrate pre-recognition which could contribute to the substrate promiscuity within
94 members of family IV (20).

95 The aim of this study was to mine carboxylic ester hydrolases of the soil rhizosphere of
96 sorghum plants after enrichment with cashew nut shell liquid (CNSL), an oily substance rich
97 in phenolics and fatty acids (21), with respect to novel biocatalysts. By applying an activity-
98 based strategy, four such enzymes were retrieved and characterized. We also reported the
99 crystal structure of one of these enzymes with an extraordinarily broad substrate specificity.
100 The structural information, complemented with the experimental analysis of the substrate
101 specificity of a series of variants, provides additional mechanistic understanding of the
102 molecular basis for the role of the cap domain in the promiscuous character of members
103 comprising family IV esterases. Importantly, we propose the role of proline residues at the N-
104 terminal region comprising α1-α2 helices as hinges of the movement of the cap domain
105 allowing substrates to enter the active center.
106
107 **Results**
108 **Identification of a carboxylic ester hydrolase.** The search for hydrolytic enzymes in the
109 metagenomics library SorRhizCNSL3 W (see details in Materials and Methods) was carried out
110 by applying a metagenomic functional screening approach. The strategy involved the use of
111 LB agar plates containing tributyrin (22). The pooling of 40 clones per well dispensed into 96-
112 well microtiter plates (approximately 3.8 k clones in one plate) facilitated the colony screening
113 at a high throughput. After screening more than 100,000 clones, 1 hit from the SorRhizCNSL3
114 W library showed lipase/esterase activity. Fosmid insert was extracted using the QUIAGEN
115 Large-Construct Kit (QIAGEN, Hilden, Germany) according to the manufacturer's protocol,
116 digested with restriction enzymes for insert size estimation, and the insert sequenced by
117 Illumina technology. Upon the completion of sequencing, the reads were quality-filtered and
118 assembled to generate nonredundant meta-sequences, and genes were predicted and

119 annotated as described previously (12). One gene encoding a predicted carboxylic ester
120 hydrolase was identified. The gene was amplified with specific primers, cloned into the
121 p15TV-L vector and transformed into *E. coli* BL21(DE3) cells for expression of the N-terminal
122 (His)6-tagged proteins. The deduced amino acid sequence of the enzyme (324 amino acids
123 long) was used for homology searches in the taxonomy and functional assignment. A database
124 search indicated that EH_0 showed 99% identity with the α/β hydrolase enzyme from
125 *Sphingomonas pruni* (protein ID WP_066587239), both of which are classified as members of
126 the α/β hydrolase-3 family (PF07859). The typical H-G-G-G motif and the G-X-S-X-G catalytic
127 motif are conserved, and EH_0 clustered together with family IV esterase.

128 **Biochemical characterization.** The recombinant protein was successfully expressed in
129 soluble form and purified by nickel affinity chromatography. Purified protein was desalted by
130 ultrafiltration, and its enzymatic activity was assessed. Four model *p*-nitrophenyl (*p*-NP) ester
131 substrates with different chain lengths were used to determine the substrate specificity of
132 the enzymes and therefore determine whether the enzymes are in fact true lipases or
133 esterases. Lipases hydrolyze ester bonds of long-chain triglycerides more efficiently than
134 esterases, which instead exhibit the highest activity toward water soluble esters with short
135 fatty acid chains (23). The substrates used for the hydrolytic test were *p*-NP acetate (C2), *p*-
136 NP butyrate (C4), *p*-NP dodecanoate (C12), and *p*-NP palmitate (C16). The hydrolytic activity
137 was recorded under standard assay conditions (Fig. 1). EH_0 showed a specific activity of 496.5
138 U mg^{-1} for *p*-NP butyrate, which was the best substrate. Lower levels of activity were observed
139 with longer chain esters (C ≥ 12). The esterase followed the Michaelis–Menten kinetics, and
140 its kinetic parameters are reflected in Table 1. A comparison of the catalytic efficiency values
141 (k_{cat}/K_M) indicated a high reactivity toward *p*-NP-butyrate followed by *p*-NP-acetate.

142 Its voluminous (volume of the active site cavity: 5133 Å^3) but low exposed (solvent
143 accessible surface area (SASA): 5.07 over 100 dimensionless percentage) active site allows
144 hydrolysis of a broad range of 68 out of 96 structurally and chemically diverse esters (Table
145 S1), as determined by a pH indicator assay (pH 8.0, 30 °C). Phenyl acetate (30.23 U mg^{-1}) and
146 glyceryl tripropionate (29.43 U mg^{-1}), were the best substrates. We also found that EH_0
147 efficiently hydrolyzed bis(2-hydroxyethyl)-terephthalate (BHET; 163.6 ± 6.2 U mg^{-1}), an
148 intermediate in the degradation of polyethylene terephthalate (PET) (24); HPLC analysis (Fig.
149 S1), performed as described (25), confirmed the hydrolysis of BHET to mono-(2-
150 hydroxyethyl)-terephthalic acid (MHET) but not to terephthalic acid (TA). However, using
151 previously described conditions (25), we found that the enzyme did not hydrolyze large
152 plastic materials such as amorphous and crystalline PET film and PET nanoparticles from
153 Goodfellow. According to the number of hydrolyzed esters, EH_0 can be thus considered as an
154 esterase with a wide substrate specificity, similar to other enzymes of the family IV (19, 20).
155 EH_0 showed maximal activity at 50 °C, retaining more than 80% of the maximum activity at
156 40-55 °C (Fig. 2A), suggesting that it is moderately thermostable. This was confirmed by
157 circular dichroism analysis, which revealed a denaturing temperature of 55.7 ± 0.2 °C (Fig. 2B).
158 Its optimal pH for activity was 9.5 (Fig. 2C). The effect on the enzymatic activity of organic
159 solvents at different concentrations was evaluated (Table S2). An activation effect was
160 observed for EH_0 when 10% methanol (60% activity increase) and 10-20% DMSO (22-40%
161 increase) were added to the reaction mixture. The presence of bivalent and trivalent cations
162 did not have a remarkable positive effect on the activity of the enzymes, which showed, in
163 some cases, tolerance to high concentrations of cations (Table S3). A prominent inhibiting
164 effect was shown for all cations, except for magnesium, which was well tolerated at 1-10 mM
165 (<5% inhibition).

166 **EH_0 presents tight folding of its cap domain.** The crystal structure of wild type EH_0 was
167 obtained at 2.01 Å resolution, with the $P2_12_12_1$ space group and two crystallography-
168 independent molecules in the asymmetric unit. Molecular replacement was performed using
169 Est8 as a template (PDB code 4YPV) (26), and the final model was refined to a crystallographic
170 R-factor of 0.1717 and R-free of 0.2019 (Table S4). As with other reported family IV esterases,
171 EH_0 has an **α/β** hydrolase fold with two different domains, a cap domain (residues 1-43 and
172 208-229) and a catalytic domain (residues 44-207 and 230-324), constituted by a total of 9 **α**-
173 helices and 8 **β**-sheets (Fig. 3A). The catalytic domain was composed of a central **β**-sheet with
174 eight parallel **β**-strands (**β**1, **β**3, **β**4, **β**5, **β**6, **β**7, **β**8), except **β**2, which was antiparallel and
175 surrounded by five **α**-helices (**α**3, **α**4, **α**5, **α**8, **α**9). The cap domain involved four **α** helices
176 (**α**1, **α**2, **α**6, **α**7) (Fig. 3B). There were two *cis* peptides, Ala122-Pro123 and Trp127-Pro128,
177 located at the **β**4-**α**4 turn within the catalytic domain.
178 Analysis of EH_0 folding using the *DALI* server (27) was employed to search for homologous
179 proteins. The closest homologs are E53 isolated from *Erythrobacter longus*, with 46% identity
180 and RMSD of 2.3 Å on 296 Cα atoms (PDB code 7W8N) (28); Est8 isolated from *Parvibaculum*,
181 with 38% identity and RMSD of 2.5Å on 291 Cα atoms (PDB code 4YPV) (26); PestE isolated
182 from *Pyrobaculum calidifontis*, with 33% identity and RMSD of 2.6Å on 294 Cα atoms (PDB
183 code 3ZWQ) (29); and EstA isolated from *Sulfolobus islandicus REY15A,* with 31% identity and
184 RMSD of 2.6Å on 281 Cα atoms (PDB code 5LK6). The structural superimposition of these
185 proteins reveals a high conservation of the corresponding catalytic domains, and also a
186 common spatial arrangement of the helices at the cap domains in all the proteins except EH_0,
187 where α2 and the long α7 are visibly shifted very close to its EH_0 active site and apparently
188 impeding the entrance of substrates (Fig. 3C). This was unexpected considering the broad
189 substrate specificity of esterase EH_0, approaching that of most promiscuous ones (19). Thus,

190 withdrawal of the cap domain seems a necessary requirement for allowing access of the bulky
191 substrates to the EH_0 catalytic site.
192 In agreement with this assumption, a substantial rearrangement of the cap domain was
193 previously described in the homolog esterase EST2 (having 31 % sequence identity), with its
194 M211S/R215L double variant being trapped in the crystal in a conformation resembling the
195 open form of lipases (30). However, the authors did not assign any biological relevance to this
196 issue, considering this state as an artifact derived from the crystal packing. In our study, some
197 flexibility at this region has been found from the two conformations adopted by loop α1-α2
198 observed in subunits A and B of EH_0 (Fig. 3D). In addition, the inspection of residues within
199 the cap domain showed a high number of proline residues (Pro8, Pro21, Pro23, Pro31, Pro46
200 and Pro47) (Fig. 3B) that are mostly non-conserved and could confer flexibility to the N-
201 terminal cap domain allowing substrate entrance. This feature will be discussed below.
202 **EH_0 is a dimeric enzyme.** While E53 and Est8 are monomeric enzymes, and EstA is a
203 tetramer, EH_0 is presented as a biological homodimer with approximate dimensions of 6.3 x
204 4.9 x 2.7 nm, which is assembled in a twofold axis symmetry arrangement (Fig. 4A) that buries
205 5.6% of its total surface area. Hydrogen bonds mainly involve β8 and α8, while salt bridges
206 involve motifs β8 and α9 (Fig. 4B and Table S5). Similar to its dimeric homolog PestE,
207 oligomerization occurs through a tight interaction of β8 strands from both subunits. However,
208 while only the subsequent helices **α**12 were involved in the PestE interface (29) (Fig. 4C), both
209 the precedent **α**8 and the subsequent **α**9 helices make the EH_0 interface (Fig. 4D). These
210 different interactions observed in PestE and EH_0 were reflected in a different orientation
211 between the monomers that, nevertheless, present a similar distance between the catalytic
212 serines of 35-38 Å and an equivalent disposition of the tunnels giving access to the catalytic
213 site at two edges of the dimer (Fig. 4E, 4F). Therefore, as seen in Fig. 4A, the two cap domains

214 are far from the interface and project out from the dimer, revealing that dimerization is not
215 affecting the cap function.

216 **The peculiar EH_0 active site.** EH_0 has a long catalytic tunnel with a very narrow entrance
217 (approximately 16.8 Å depth) (Fig. 5A). The catalytic triad of EH_0 is formed by Ser161 (in the
218 conserved motif ^{159}G-D-S-A-G^{163} in the nucleophilic elbow), Asp253 (in the conserved motif
219 ^{253}D-P-I-R-D^{258}) and His283 (Fig. 5B). To analyze the active site, a series of soaking and
220 cocrystallization experiments were performed with different suicide inhibitors, all of which
221 were unsuccessful. A deep inspection of the active site showed that the nucleophilic Ser161
222 is hydrogen bonded to Glu226 from the close **α**7, and a movement of loop **β**3-**α**3, including
223 the oxoanion in the conserved motif ^{87}H-G-G-G^{90,} compared to EH_0 homologs (Fig. 5B).
224 Therefore, to remove this hydrogen link in an attempt to expand access to the active site
225 enabling ligand binding, the EH_{0E226A} variant was produced by directed mutagenesis.
226 However, the crystals grown from this variant failed to diffract, suggesting a high level of
227 disorder, putatively due to an increased mobility of the cap. Interestingly, the activity profile
228 of this variant reveals a faster hydrolysis of most of the esters (62 esters in total; from 70- to
229 1.2-fold; average: 6.1-fold). Only 7 esters were hydrolyzed to a lower extent compared to the
230 wild type (from 1.5- to 17-fold; average: 4.6-fold). Remarkably, the EH_{0E226A} variant was
231 capable of accepting large and voluminous esters such as dodecanoyl acetate, pentadecyl
232 acetate, vinyl laurate, methyl 2,5-dihydroxycinnamate, and ethyl 2-chlorobenzoate, which
233 were not accepted by the wild-type enzyme (Table S1). This apparently supports that removal
234 of the Ser161-Glu226 hydrogen bond increases cap flexibility and enhances the enzymatic
235 efficiency toward large esters either at the acyl or alcohol sites.

236 Indeed, it appears clear that helix α7 must retract from the catalytic site to allow substrate
237 entrance, but this helix seems fixed by many atomic interactions. Close to the Ser161-Glu226

238 hydrogen bond, Tyr223 makes additional hydrogen bonds to Asp194 and Lys197 main chain,
239 from loop β6-α6, and with the side chain of Gln258 from α8 (Fig. 5C). A mutation EH_{0Y223A} was
240 generated by directed mutagenesis and found, unlike the EH_{0E226A} mutation, little effect on
241 conversion rates compared to the wild-type enzyme. However, this mutation allowed the
242 hydrolysis of large and voluminous esters, such as dodecanoyl acetate, pentadecyl acetate,
243 methyl 2,5-dihydroxycinnamate and ethyl 2-chlorobenzoate, which were also hydrolyzed by
244 the variant EH_{0E226A}. Unlike EH_{0E226A}, the EH_{0Y223A} variant was not unable to hydrolyze vinyl
245 laurate, but it was able to hydrolyze methyl 3-hydroxybenzoate, not accepted by the EH_{0E226A}
246 variant. This suggested that Tyr223 may play a role in accepting large esters, particularly at
247 the acyl side, but may also play an additional role in substrate specificity different from that
248 of Glu226.

249 Additionally, at the beginning of α7, Trp218 is within a hydrophobic pocket surrounded by
250 residues Phe13, Ile17, Leu28 and Phe219 from the cap domain and Phe91 from the catalytic
251 domain, which is also anchored by interaction with loop α1-α2 and Pro23 (Fig. 5D). Thus, to
252 depict how these tight molecular packing may be disrupted by the proposed cap motion,
253 molecular dynamics were applied to crystallographic refinement through the ensemble
254 refinement strategy, which is shown to model the intrinsic disorder of macromolecules giving
255 more accurate structures. The ensemble models obtained for molecules A and B within the
256 asymmetry unit are shown in Fig. 5E and 5H, respectively. The analysis of the molecule A
257 conformers (Fig. 5E) revealed that the region comprising α1 and α2 shows a wide spectrum
258 of possible pathways from more "open" to more "closed" conformations. At one edge, Pro23
259 is in an extended α1-α2 loop far from Trp218, therefore releasing α7 that consequently could
260 retract from the catalytic pocket ("open-like conformation") (Fig. 5F). In fact, the ensemble
261 refinement models a very flexible conformation being even unstructured at regions

262 corresponding to α1 and α2. At the other edge, the second scenario is the entrapment of
263 Trp218 by Pro23 in loop α1-α2, hindering substrate entrance ("closed-like conformation")
264 (Fig. 5G). This last scenario is equivalent to the 3D structure captured by crystallography (Fig.
265 5D). Furthermore, three prolines can be found within this α1-α2 loop, Pro21 (at the end of
266 α1), Pro23 (at the middle) and Pro31 (at the beginning of α2), all of them unique to EH_0, which
267 are probably behind the two different conformations observed at this loop in both subunits
268 within the asymmetric unit (Fig. 3B and 3D), and explain the ensemble of conformers
269 modelled for molecule B (Fig. 5H).

270 Furthermore, as seen in Fig. 3B, Pro46 and Pro47 are potential hinges that would involve
271 flexibility of a larger region of the EH_0 cap domain, including the whole N-terminal peptide
272 chain up to the end of α2. This is consistent with the more "open" conformations resulting
273 from the ensemble refinement shown in Fig. 5F. In fact, the sequence comparison of EH_0 to
274 its closest homologs reveals that only EH_0 has two sequential prolines at this region and that
275 Pro46 is unique to EH_0 (Fig. 6), which could be a reason behind the high EH_0 promiscuity.
276 Interestingly, EST2 also presents the two contiguous Pro residues (Pro38, Pro39), which can
277 also confer high mobility to its cap domain and facilitate the "open-like" conformation
278 captured in the crystal mentioned above (30). Therefore, the mutation EH_{0P46A} was generated
279 by directed mutagenesis and submitted to crystallization experiments to investigate the
280 Pro46 putative role. However, the crystals grown from this variant EH_{0P46A} failed to diffract,
281 suggesting that removal of Pro46 introduces some structural instability to the polypeptide
282 chain resulting in crystal disorder. Moreover, analysis of the activity profile showed that Pro46
283 is a critical residue for the entry and hydrolysis of bulky substrates, as its mutation by Ala
284 extends the substrate specificity from 68 to 84 esters. Additionally, the hydrolytic rate
285 increased from 1.2- to 18000-fold (average: 335-fold) for most esters. This variant was also

286 able to hydrolyze large glyceryl trioctanoate and 2,4-dichlorophenyl 2,4-dichlorobenzoate,
287 which were not hydrolyzed by the wild-type enzyme or the EH_{0E226A} and EH_{0Y223A} variants.
288 Consequently, although the proposed role of Pro46 and Pro47 as putative hinges enabling the
289 opening of the cap domain seems appealing, other mechanisms promoting EH_0 plasticity to
290 bulky substrates may also operate. Furthermore, as seen below, it should be noted that the
291 two proline residues are located at the entrance of the narrow tunnel giving access to the
292 active-site, an issue that ascribes a prominent role to both residues in binding activity and
293 specificity.

294 Structural details of the EH_0 active site and assignment of the acyl and alcohol moieties
295 were explored by comparison with its homologs E53 complexed with 4-nitrophenyl
296 hexanoate (PDB code 6KEU) (28) and EH_{1AB1} in complex with a derivative of methyl 4-
297 nitrophenylhexylphosphonate (PDB code 6RB0) (31). However, the acyl and alcohol moieties
298 of these complexes are located in opposite sites (Fig. 5I, 5J). Therefore, as we could not obtain
299 complexes from EH_0, the activity experiments were crucial to correctly assign acyl/alcohol
300 moieties. As mentioned above, experimental evidence demonstrated that Tyr223 produces a
301 steric hindrance at the acyl moiety, and consequently, the acyl and alcohol sites correspond
302 to those observed in EH_{1AB1} (Fig. 5J). On the basis of this assumption, the acyl binding site
303 seems to be a small cavity bordered by the Tyr199 and Ile255 side chains, which produce
304 steric hindrance for substrates with large acyl moieties. The long and narrow alcohol binding
305 site is surrounded by both hydrophobic (Phe13, Phe91, Val92, Leu288) and hydrophilic
306 residues (Asp45, His99, Asp160, Tyr190, Thr287), with Pro46 and Pro47 being at the entrance
307 of the tunnel (Fig. 5K). Most residues at the acyl and alcohol moieties are conserved among
308 EH_0 homologs, with the exception of Met40, Pro46, Tyr199, Glu226 and Thr287. Remarkably,
309 the bulky Met40 and Tyr199 residues are substituted by smaller residues in the EH_0 homologs.

310 As previously mentioned, Pro46 is unique in EH_0, while Glu226 is substituted by a conserved
311 Asp, and finally, most homologs show an Asn residue instead of Thr287 (Fig. 6). Therefore, as
312 the retraction of the cap domain must be performed to allow substrate entrance, residues
313 Phe91, Tyr190 and Tyr199 from the catalytic domain, which are located close to the catalytic
314 triad, seem essential for substrate specificity (Fig. 5K).
315
316 **DISCUSSION**
317 In this study, the microbial community of the *Sorghum bicolor* rhizosphere was exposed to
318 a chemical treatment prior to eDNA extraction to construct a metagenomic library. Plant roots
319 can secrete exudates composed of a large variety of compounds into the soil, some of which
320 may play important roles in the rhizosphere (32, 33), and with effects that involve multiple
321 targets, including soil microorganisms. This is why an amendment of the soil with technical
322 cashew nut shell liquid (tCNSL), containing a mixture of phenolic compounds with long
323 aliphatic side chains (up to C22:0), was carried out directly in the rhizosphere and, later, for
324 three weeks under control laboratory conditions, as we were interested in screening lipolytic-
325 like activity. By applying metagenomics techniques we retrieved an esterase, EH_0, highly
326 similar (99% identity) to the predicted α/β hydrolase from the genome of *S. pruni* (acc. nr.
327 WP_066587239). The most homologous, functionally characterized protein is actually
328 P95125.1, a carboxylic ester hydrolase LipN from *Mycobacterium tuberculosis* H37Rv, which
329 shows only 41% amino acid sequence identity with EH_0. That said, given the high identity of
330 WP_066587239 and EH_0 we expect both hydrolases having similar properties, yet to be
331 experimentally confirmed. Indeed, we observed that there are only three changes in their
332 sequences, which are located on the outside and in loops away from the key residues and the
333 dimerisation interface (Fig. S2).

334 EH_0 was classified within the previously described hormone-sensitive lipase (HDL) type IV
335 family, that is one of the at least 35 families and 11 true lipase subfamilies known to date (10,
336 23, 34). This family is reported to contain ester hydrolases with relative SASA values ranging
337 from 0 to 10% and high levels of substrate specificity (19). Note that SASA, computed as a
338 (dimensionless) percentage (0−1 or 0-100) of the ligand SASA in solution (19), is a parameter
339 that inspect the solvent exposure of the cavity containing the catalytic triad and the capacity
340 of a cavity to retain/stabilize a substrate (19). For example, a SASA of 40% (over 100%) implies
341 that 40% of the surface is accessible to the solvent, which facilitates the escape of the
342 substrate to the bulk solvent; this is the case of enzymes with active site in the surface where
343 the catalytic triad is highly exposed. By contrast, enzymes that has a larger but almost fully
344 occluded site that can better maintain and stabilize the substrate inside the cavity, are
345 characterized by relative SASA values of approximately 0−10%. This is the case of EH_0, which
346 has a SASA of 5.07% because a large but almost fully occluded active site, an architecture that
347 is known to better maintain and stabilize a higher number of substrates inside the cavity (19).
348 Indeed, this enzyme houses a very long and narrow catalytic pocket, where helix α7 is very
349 close to the catalytic triad with residue Glu226, making a direct hydrogen bond to the catalytic
350 nucleophile Ser161. Therefore, it appeared clear that the cap domain must retract to allow
351 substrate entrance to the active site. The movement of this domain was modeled by
352 combining X-ray diffraction data with molecular dynamics simulation through the ensemble
353 refinement procedure. This strategy showed a broad range of putative conformations at the
354 cap domain, with Pro46 and Pro47 likely acting as hinges conferring a high plasticity to the N-
355 terminal region of the cap. Remarkably, the presence of a number of prolines at this region
356 particularly these two sequential prolines, is a unique feature of EH_0 compared to its
357 homologs, and other substrate-promiscuous members of the family IV (19). Mutational

358 analysis confirmed the role of one of these prolines in the access and hydrolysis of large and
359 voluminous substrates and thus in the increase in the substrate promiscuity level.
360 The above structural features differ from those of other substrate promiscuous family IV
361 esterases, tested over the same set of ester substrates, namely, EH_{1AB1} (31), and EH_3 (35, 36)
362 capable of hydrolyzing a similar number of esters. The comparison of EH_{1AB1} and EH_3 with EH_0,
363 shows major differences related to the *lid* (Fig. 7A). Whereas EH_{1AB1} and EH_3 show large and
364 wide catalytic pockets with two possible access to the binding site (Fig. 7B and C), EH_0 has a
365 unique, narrow and long entrance to the catalytic active site, as said before (Fig. 7D).
366 Therefore, in the case of EH_0 only a structural rearrangement of the cap domain would allow
367 its adaptation to all different substrates, which likely implies that the cap domain of EH_0
368 exhibits more flexibility than those from EH_{1AB1} and EH_3. This is consistent with the fact that
369 of the 80 esters that the three enzymes together are able to hydrolyze, 61 (or 76%) were
370 common to all three, and that EH_0 was the only one able to hydrolyze such bulky substrates
371 as 2,4-dichlorobenzyl 2,4-dichlorobenzoate or diethyl-2,6-dimethyl 4-phenyl-1,4-dihydro
372 pyridine-3,5-dicarboxylate.
373 Biochemical characterization of the novel esterase also revealed that the activity or EH_0
374 was in most cases stimulated in the presence of 10% organic solvents, particularly in 10%
375 methanol and DMSO. Such activation is also a characteristic of some lipases. For example, the
376 analysis of the lipase from *Thermus thermophilus* revealed that although the overall structure
377 was maintained stable with or without polar organic solvent, the lid region was more flexible
378 in the presence of the later. The flexible lid facilitates the substrate to access the catalytic site
379 inside the lipase and the lipase displays enhanced activity in the presence of a polar organic
380 solvent (37). The use of organic solvents offers more advantages over canonical aqueous
381 biocatalysis for various reasons: higher solubility of hydrophobic substrates, minor risk of

382 contamination, and higher thermal stability (38-40). EH_0 has a potential advantage in
383 applications that require alkaline conditions due to its ability to act at the optimal pH of 9.0.
384 Temperature-controlled tests indicated a mesophilic/slightly thermophilic profile of the
385 esterase as expected from the original habitat at moderate temperatures. In addition, the
386 structure of EH_0 is similar (31-33% identity) to those of extremophiles, namely, *Pyrobaculum*
387 (3ZWQ) and *Sulfolobus* (5LK6) species.

388 In summary, the present study evaluated the conformational plasticity of the cap domain
389 in members of Family IV, and the role of several non-conserved prolines as putative structural
390 factor regulating their broader substrate specificity compared to other members of the 35
391 families and 11 true lipase subfamilies reported (10). This high molecular flexibility is markedly
392 different to that found in other family IV esterases and a family VIII β-lactamase fold hydrolase
393 (EH_7) which has been recently shown to be highly substrate-promiscuous. In this case, the
394 broad substrate specificity is given by the presence of a more opened and exposed S1 site
395 having no steric hindrance for the entrance of substrates to the active site, and more flexible
396 R1, R2 and R3 regions allowing the binding of a wide spectrum of substrates into the active
397 site.

398

399 **CONCLUSIONS**

400 Activity-based metagenomics approach was used to study the microbial enzyme diversity
401 in rhizosphere soil of *Sorghum* plants amended with CNSL soil. A novel esterase was found,
402 which possessed a broad substrate promiscuity in combination with a significant pH and
403 solvent tolerance. This work is crucial for deciphering structural markers responsible for the
404 outstanding broad substrate specificity of EH_0. Indeed, this work further provides important

405 insights into the role of cap domains and its contribution to the diverse selectivity profiles and
406 thus versatility of family IV esterases/lipases toward the conversion of multiple substrates.
407
408 **MATERIALS AND METHODS**
409 **Plant material and outdoor seed germination.** Seeds of *Sorghum bicolor* genotype BTx623
410 were obtained from the Agricultural Research Service of United States Department of
411 Agriculture (USDA) (Georgia, US) as a gift. Field soil was sampled from the Henfaes Research
412 Centre (53°14'21.0"N, 4°01'06.5"W, Gwynedd, Wales) in September 2014. The soil sample
413 was composed of a mixture of five topsoil samples collected from randomly selected positions
414 in the field. The soil was air-dried, mixed thoroughly, and stored at room temperature for use
415 in subsequent experiments. Two L pots were filled with soil, and two seeds of *S. bicolor*
416 BTx623 were planted per pot. Plants were cultivated in a greenhouse at 20 °C, and the soil
417 moisture content was maintained with tap water.
418 **Enrichment with CNSL.** Three grams of technical cashew nut shell liquid (tCNSL) dissolved
419 in 70% ethanol was added to a pot of 20-day-old plants and thoroughly mixed with the soil.
420 After 60 days, plants were pulled out of the pot, and the soil was shaken off; samples of
421 rhizosphere soil attached to the plant roots were then brushed off and collected. tCNSL was
422 provided by the BioComposites Centre at Bangor University (Wales, UK). Three biological
423 replicates of laboratory microcosm enrichment were set up in conical 1 L Erlenmeyer flasks
424 by mixing 10 g of the collected rhizosphere soil with 300 mL of sterile Murashige Skoog Basal
425 medium (Sigma) and 10 mg/L cycloheximide. tCNSL was dissolved in 70% ethanol and added
426 to the medium to a final concentration of 0.1 g/L; flasks were incubated at 20 °C in an orbital
427 shaker. 50 g of oil slurry was sampled every seven days, and fresh tCNSL-containing (0.1 g/kg)
428 medium was added to replace the volume of the medium.

429 **Extraction of DNA and generation of metagenomic library.** Samples collected after 3
430 weeks of flask microcosm enrichment were used for the construction of fosmid metagenomic
431 libraries. Environmental DNA was extracted using the Meta-G-Nome DNA Isolation Kit
432 (Epicenter Biotechnologies; WI, USA) according to the manufacturer's instructions. Briefly, 50
433 ml of the soil suspension from the flask enrichment was centrifuged at 400 x g for 5 min. The
434 supernatant was filtered through 0.45 µm and 0.22 µm membrane filters. This procedure was
435 repeated with the initial soil sample four times: the remaining soil was resuspended in PBS
436 and centrifuged, and the supernatant was filtered as before. Filters were combined, and the
437 sediment on the filter was resuspended in extraction buffer and collected. DNA extraction
438 was carried out according to the protocol described by the manufacturer. The quality of the
439 extracted DNA was evaluated on agarose gel and quantified with the Quant-iT dsDNA Assay
440 Kit (Invitrogen) on a Cary Eclipse fluorimeter (Varian/Agilent) according to the manufacturer's
441 instructions. The extracted metagenomic DNA was used to prepare two different
442 metagenomic fosmid libraries using the CopyControl™ Fosmid Library Production Kit
443 (Epicenter). DNA was end-repaired to generate blunt-ended, 5'-phosphorylated double-
444 stranded DNA using reagents included in the kit according to the manufacturer's instructions.
445 Subsequently, fragments of 30-40 kb were selected by electrophoresis and recovered from a
446 low melting point agarose gel using GELase 50X buffer, and GELase enzyme preparation was
447 also included in the kit. Nucleic acid fragments were then ligated to the linearized CopyControl
448 pCC2FOS vector in a ligation reaction performed at room temperature for 4 hours, according
449 to the manufacturer's instructions. After in vitro packaging into phage lambda (MaxPlax™
450 Lambda Packaging Extract, Epicenter), the transfected phage T1-resistant EPI300™-T1R *E. coli*
451 cells were spread on Luria-Bertani (LB) agar medium (hereinafter, unless mentioned
452 otherwise, the agar content was 1.5% w/vol) containing 12.5 µg/ml chloramphenicol and

453 incubated at 37 °C overnight to determine the titer of the phage particles. The resulting
454 library, SorRhizCNSL3 W, has an estimated titer of $1.5x10^6$ clones. For long-term storage, the
455 library was plated onto solid LB medium with 12.5 µg/ml chloramphenicol, and after
456 overnight growth, colonies were washed off from the agar surface using LB broth with 20%
457 (v/v) sterile glycerol, and aliquots were stored at −80 °C.

458 **Screening metagenomic libraries: agar-based methods.** Fosmid clones obtained by plating
459 the constructed libraries on LB agar plates were arrayed in 384-microtiter plates (1
460 clone/well) or alternatively in 96-microtiter plates (pools of approximately 40 clones/well)
461 containing LB medium and chloramphenicol (12.5 µg/ml). The plates were incubated at 37 °C
462 overnight, and the day after replication, the plates were produced and used in the screening
463 assay. Glycerol (20% v/v, final concentration) was added to the original plates, which were
464 stored at -80 °C. Gel diffusion and colorimetric assays were adopted for the screening of the
465 desired activities. The detection of lipase/esterase activity was carried out on LB agar
466 supplemented with chloramphenicol (12.5 µg/ml), fosmid autoinduction solution (2 ml/L)
467 (Epicenter), and 0.3% (v/v) tributyrin emulsified with gum arabic (2:1, v/v) by sonication. The
468 previously prepared microtiter plates were printed on the surface of large (22.5 cm x 22.5 cm)
469 LB agar plates using 384-pin polypropylene replicators and incubated for 18-48 hours at 37
470 °C. Lipolytic activity was identified as a clear zone around the colonies where tributyrin was
471 hydrolyzed (12).

472 **Extraction of fosmids, DNA sequencing and annotation.** The fosmid DNA of the positive
473 clone was extracted using the QIAGEN Plasmid purification kit (QIAGEN). To reduce the host
474 chromosomal *E. coli* DNA contamination, the sample was treated with ATP-dependent
475 exonuclease (Epicenter). The purity and approximate size of the cloned fragment were
476 assessed by agarose gel electrophoresis after endonuclease digestion simultaneously with

477 *BamHI* and *XbaI* (New England Biolabs, in NEBuffer 3.1 at 37° for 1 hour using 1 U of enzyme
478 per 1 µg DNA). DNA concentration was quantified using the Quant-iT dsDNA Assay Kit
479 (Invitrogen), and DNA sequencing was then outsourced to Fidelity Systems (NJ, USA) for
480 shotgun sequencing using the Illumina MiSeq platform. GeneMark software (41) was
481 employed to predict protein coding regions from the sequences of each assembled contig,
482 and deduced amino acid sequences were annotated via BLASTP and the PSI-BLAST tool (42).
483 **Cloning, expression and purification of proteins.** The selected nucleotide sequence was
484 amplified by PCR using Herculase II Fusion Enzyme (Agilent, USA) with specific oligonucleotide
485 primer pairs incorporating p15TV-L adapters. The corresponding fosmid was used as a
486 template to amplify the target genes. The primers used to amplify the esterase gene
487 characterized in this study were as follows: EH_{0F},
488 TTGTATTTCCAGGGCATGACCGAGCTCTTCGTCCGC; EH_{0R},
489 CAAGCTTCGTCATCATGCCGCCGCCTGTGCCATC. PCR products were visualized on a 1% TAE
490 agarose gel and purified using the Nucleospin PCR Clean-up Kit (Macherey-Nagel) following
491 the manufacturer's instructions. Purified PCR products were cloned into the p15TV-L vector,
492 transformed into *E. coli* NovaBlue GigaSingles™ Competent Cells (Novagen, Germany) and
493 plated on LB agar with 100 µg/ml ampicillin. The correctness of the DNA sequence was then
494 verified by Sanger sequencing at Macrogen Ltd. (Amsterdam, The Netherlands). 3-D models
495 of the proteins were generated by Phyre2. The intensive mode attempts to create a complete
496 full-length model of a sequence through a combination of multiple template modeling and
497 simplified ab initio folding simulation (43). The nucleotide and amino acid sequences of the
498 selected nucleotide sequences are available GenBank under ref. MK791218. For recombinant
499 protein expression, the plasmids were transformed into *E. coli* BL21(DE3) cells and
500 subsequently plated on LB agar with 100 µg/ml ampicillin. To confirm the esterase activity of

501 recombinant proteins, *E. coli* clones harboring the recombinant plasmid were streaked onto
502 LB agar plates containing 0.5% tributyrin and 0.5 mM IPTG, or purified enzymes were spotted
503 directly on the agar. The plates were then incubated at 37 °C overnight and visually inspected
504 for the presence of signs of substrate degradation. *E. coli* clones were grown at 37 °C to an
505 absorbance of 0.8 at 600 nm, induced with 0.5 mM isopropyl-β-D-galactopyranoside (IPTG),
506 and allowed to grow overnight at 20 °C with shaking. Cells were harvested by centrifugation
507 at 5000 x g for 30 min at 4 °C. For purification of recombinant protein, the following protocol
508 was applied. Cell pellets were resuspended in cold binding buffer (50 mM HEPES pH 7.5, 400
509 mM NaCl, 5% glycerol, 0.5% Triton-X, 6 mM imidazole pH 7.5, 1 mM β-mercaptoethanol, 0.5
510 mM PMSF) and extracted by sonication. The lysates were then centrifuged at 22,000 x g for
511 30 min at 4 °C, and the supernatant was purified by affinity chromatography using Ni-NTA His-
512 bind resin (Novagen). The column packed with the resin was equilibrated with binding buffer,
513 and after the addition of supernatant, it was washed with 6 volumes of wash buffer (50 mM
514 HEPES pH 7.5, 400 mM NaCl, 5% glycerol, 0.5% Triton-X, 26 mM imidazole pH 7.5, 1 mM β-
515 mercaptoethanol, 0.5 mM PMSF) to remove nonspecifically bound proteins. His-tagged
516 proteins were then eluted with elution buffer (50 mM HEPES pH 7.5, 400 mM NaCl, 5%
517 glycerol, 0.5% Triton-X, 266 mM imidazole pH 7.5, 1 mM β-mercaptoethanol, 0.5 mM PMSF).
518 The size and purity of the proteins were estimated by SDS–PAGE. Protein solutions were
519 desalted through the Amicon Ultra15 10K centrifugal filter device. Protein concentrations
520 were determined using the Bradford Reagent (Sigma) and the BioMate™ 3S
521 spectrophotometer (Thermo Scientific, USA).

522 **Biochemical assays.** Hydrolytic activity was determined by measuring the amount of *p*-
523 nitrophenol released by catalytic hydrolysis of *p*-nitrophenyl (*p*-NP) esters through a modified
524 method of Gupta et al. (44). Stock solutions of *p*-NP esters (100 mM *p*-NP acetate, 100 mM *p*-

525 NP butyrate, 20 mM *p*-NP dodecanoate, and 20 mM *p*-NP palmitate) were prepared in
526 DMSO/acetonitrile (1:1 v/v). Unless stated otherwise, the enzymatic assay was performed
527 under standard conditions in a 1 ml reaction (50 mM potassium phosphate buffer pH 7.0,
528 0.3% (v/v) Triton X-100, 1 mM substrate) under agitation in a water bath at 50 °C until
529 complete substrate solubilization (note: solvents were present in the assays at a
530 concentration of 1% for 100 mM-stocks of *p*-NP butyrate and acetate, or 5% for 20 mM-stocks
531 of *p*-NP dodecanoate and palmitate). After that, the multititre plate was pre-incubated at 30
532 ºC for 5 minutes in a BioMate^{TM} 3S spectrophotometer (Thermo Scientific, USA), which was
533 set up at this temperature, and then an appropriate volume of purified enzyme containing
534 0.25 µg was added to start the reaction. The reaction mixture was incubated at 30 °C for 5
535 min and then measured at 410 nm in BioMate^{TM} 3S spectrophotometer (Thermo Scientific,
536 USA). The incubation time for *p*-NP dodecanoate and *p*-NP palmitate was extended to 15
537 minutes. All experiments were performed in triplicate, and a blank with denatured enzyme
538 was included. The concentration of product was calculated by linear regression equation
539 given on the standard curve performed by the reference compound *p*-nitrophenol (Sigma).
540 One unit of enzyme activity was defined as 1 µmol of *p*-nitrophenol produced per minute
541 under the assay conditions.

542 Kinetic parameters were determined under standard conditions and calculated by
543 nonlinear regression analysis of raw data fit to the Michaelis–Menten function using
544 GraphPad Prism software (version 6.0). For the kinetics with *p*-NP butyrate and acetate the
545 concentrations were set up to 0.1, 0.5, 1, 2 and 10 mM, using stock concentrations of 100 mM
546 in DMSO/acetonitrile (a maximum concentration of 5% DMSO/acetonitrile, was used in the
547 assay). For *p*-NP dodecanoate, a concentration of 0.05, 0.1, 0.5, 1, 2 and 3 mM was used, with
548 stock concentration of 20 mM substrate (a maximum concentration of 7.5%

549 DMSO/acetonitrile, was used in the assay). Raw data, and information about precision and
550 calculations are provided in Table S6.

551 The optimal pH for enzyme activity was evaluated with *p*-NP butyrate by performing the
552 assay in different buffers, specifically 20 mM sodium acetate buffer (pH 4.0), sodium citrate
553 buffer (pH 5.5), potassium phosphate buffer (pH 7.0), and Tris-HCl (pH 8.0-9.0). The enzyme
554 reactions were stopped by adding 1 ml of cold stop solution (100 mM K-phosphate buffer pH
555 7.0, 10 mM EDTA) to neutralize the pH and avoid changes in the equilibrium between *p*-
556 nitrophenol and the deprotonated form *p*-nitrophenoxide, which would result in a decrease
557 in absorption at the applied wavelength of 410 nm (45). The optimal enzymatic temperature
558 was investigated with *p*-NP butyrate by performing the hydrolytic assay at different
559 temperatures under standard conditions (see above). To determine the denaturation
560 temperature, circular dichroism (CD) spectra were acquired between 190 and 270 nm with a
561 Jasco J-720 spectropolarimeter equipped with a Peltier temperature controller in a 0.1-mm
562 cell at 25 °C. The spectra were analyzed, and melting temperature (T_m) values were
563 determined at 220 nm between 10 and 85 °C at a rate of 30 °C per hour in 40 mM HEPES
564 buffer at pH 7.0. CD measurements were performed at pH 7.0 and not at the optimal pH (8.5-
565 9.0) to ensure protein stability. A protein concentration of 0.5 $mg \cdot mL^{-1}$ was used. T_m (and the
566 standard deviation of the linear fit) was calculated by fitting the ellipticity (mdeg) at 220 nm
567 at each of the different temperatures using a 5-parameter sigmoid fit with SigmaPlot 13.0.

568 Stability in organic solvents was assayed with *p*-NP butyrate under standard conditions in
569 the presence of 10-20-40-60% (v/v) of the water-miscible organic solvents ethanol, methanol,
570 isopropanol, acetonitrile, DMSO, and a mixture acetonitrile/DMSO (50% each). The effect of
571 cations was investigated with *p*-NP butyrate under standard conditions by the addition of
572 $MgCl_2$, $CuCl_2$, $FeCl_3$, $CoCl_2$, $CaCl_2$, $MnCl_2$, and $ZnSO_4$ at concentrations in the range of 1 to 10

573 mM. In all cases, the measured values were then expressed as the relative activity in
574 comparison to the control reaction performed under standard conditions.

575 The hydrolysis of esters other than *p*-NP esters, including bis(2-hydroxyethyl)-
576 terephthalate (BHET), was assayed using a pH indicator assay in 384-well plates at 30 °C and
577 pH 8.0 in a Synergy HT Multi-Mode Microplate Reader in continuous mode at 550 nm over 24
578 h (extinction coefficient of phenol red, 8450 $M^{-1}cm^{-1}$). The acid produced after ester bond
579 cleavage by the hydrolytic enzyme induced a color change in the pH indicator that was
580 measured at 550 nm. The experimental conditions were as detailed previously (35), with the
581 absence of activity defined as at least a twofold background signal. Briefly, the reaction
582 conditions for 384-well plates (ref. 781162, Greiner Bio-One GmbH, Kremsmünster, Austria)
583 were as follows: protein, 0.2-2.0 µg per well; ester, 20 mM; T: 30 °C; pH, 8.0 (5 mM 4-(2-
584 hydroxyethyl)-1-piperazinepropanesulfonic acid (EPPS) buffer, plus 0.45 Phenol Red®);
585 reaction volume, 40 µl. The reactions were performed in triplicate, and datasets were
586 collected from a Synergy HT Multi-Mode Microplate Reader with Gen5 2.00 software (Biotek).
587 One unit (U) of enzyme activity was defined as the amount of enzyme required to transform
588 1 µmol of substrate in 1 min under the assay conditions. Raw data, and information about
589 precision and calculations are provided in Table S7.

590 **Crystallization and X-ray structure determination of EH_0.** Initial crystallization conditions
591 were explored by high-throughput techniques with a NanoDrop robot (Innovadyne
592 Technologies) using 24 $mg{\cdot}mL^{-1}$ protein concentrations in HEPES (40 mM, pH 7, NaCl 50 mM),
593 protein reservoir ratios of 1:1, 1.5:1 and 2:1, and commercial screens Crystal Screen I and II,
594 SaltRx, Index (Hampton Research), JBScreen Classic, JBScreen JCSG, JBScreen PACT (Jena
595 Bioscience). Further optimizations were carried out, and bar-shaped crystals of EH_0 were
596 grown after one day of mixing 1.2 µL of a mixture of protein (1 µL, 24 $mg{\cdot}mL^{-1}$) and seeds (0.2

597 µL, 1:100) with guanidine hydrochloride (0.2 µL, 0.1 M) and reservoir (0.5 µL, 11%
598 polyethylene glycol 8000, 100 mM Bis-Tris pH 5.5, 100 mM ammonium acetate). For data
599 collection, crystals were transferred to cryoprotectant solution consisting of mother liquour
600 and glycerol (20% (v/v)) before being cooled in liquid nitrogen. Diffraction data were collected
601 using synchrotron radiation on the XALOC beamline at ALBA (Cerdanyola del Vallés, Spain).
602 Diffraction images were processed with XDS (46) and merged using AIMLESS from the CCP4
603 package (47). The crystal was indexed in the $P2_12_12_1$ space group, with two molecules in the
604 asymmetric unit and 62% solvent content within the unit cell. The data collection statistics
605 are given in Table S4. The structure of EH_0 was solved by molecular replacement with MOLREP
606 (48) using the coordinates from Est8 as a template (PDB Code 4YPV). Crystallographic
607 refinement was performed using the program REFMAC (49) within the CCP4 suite, with NCS
608 (noncrystallography symmetry) medium restraints and excluding residues 17-36. The free *R*-
609 factor was calculated using a subset of 5% randomly selected structure-factor amplitudes that
610 were excluded from automated refinement. Subsequently, heteroatoms were manually built
611 into the electron density maps with Coot8 (50), and water molecules were included in the
612 model, which, combined with more rounds of restrained refinement, reached the *R* factors
613 listed in Table S4. The figures were generated with PyMOL. The crystallographic statistics of
614 EH_0 are listed in Table S4. To extract dynamical details from the X-ray data, the coordinates
615 of EH_0 were first refined using PHENIX (51) and then were used as input models for a time-
616 averaged molecular dynamics refinement as implemented in the Phenix.ensemble-
617 refinement routine, which was performed as described previously (52).

618 **Codes and accession numbers.** The sequence encoding EH_0 was deposited in GenBank
619 with the accession number MK791218. The atomic coordinates and structure factors for the
620 EH_0 structure have been deposited in the RCSB Protein Data Bank with accession codes 7ZR3.

SUPPLEMENTARY MATERIAL

Supplemental material is available online only.

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We declare no conflict of interest.

P.N.G., M.F. and J.S-A. developed the conceptual framework, M.D., C.C., T.N.C. and H.T. developed the experimental design, I.C-R. and J.S-A. performed the crystallization and X-ray structure determinations, analysis and interpretation, M.D., M.F. and P.N.G. interpreted the experimental data, P.N.G., M.F. and J.S-A. wrote the initial manuscript. All authors edited the manuscript. All authors read and approved the final manuscript.

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784

785 TABLE 1. Kinetic parameters of EH_0 against *p*NP-esters. The results are the mean ± SD of triplicates.

Substrate[1]	K_M (mM)	V_{max} (µM min^{-1})	k_{cat} (min^{-1})	k_{cat}/K_M (s^{-1} mM^{-1})
p-NP acetate	1.61 ± 0.12	291.50 ± 7.62	41.64 ± 1.09	0.430
p-NP butyrate	1.08 ± 0.18	252.60 ± 13.84	36.09 ± 1.98	0.558
p-NP dodecanoate	1.00 ± 0.28	25.56 ± 1.80	3.65 ± 0.26	0.061

786 [1]Assays were performed in the presence of 5.0-7.5% DMSO/acetonitrile (see Materials and
787 Methods), concentration at which the enzyme 100% of its activity compared to a control
788 without solvent (Table S2).
789

790 Figure Legends

791

792 FIG 1. Substrate selectivity of EH_0 against a set of model *p*-NP esters of different acyl chain lengths. Specific
793 activities (mean ± SD of triplicates) are shown. Reactions contained 1 mM of the corresponding *p*-NP esters and
794 were conducted in the presence of 1-5% DMSO/acetonitrile (see Methods), under standard conditions described
795 in Materials and Methods. At the solvent concentration used the enzyme 100% of its activity compared to a
796 control without solvent (Table S2).

797

798 FIG 2. Optimal parameters for the activity and stability of purified EH_0. (A) Temperature profile. (B) The thermal
799 denaturation curve of EH_0 at pH 7.0 was measured by ellipticity changes at 220 nm and obtained at different
800 temperatures. (C) The pH profile. The maximal activity was defined as 100%, and the relative activity is shown as
801 the percentage of maximal activity (mean ± SD of triplicates) determined under standard reaction conditions
802 with *p*-NP butyrate as the substrate. Graphics were created with SigmaPlot version 14.0 (the data were not fitted
803 to any model).

804

805 FIG 3. A) Topology diagram of EH_0. The catalytic triad is highlighted in violet. B) EH_0 folding, with the cap domain
806 in yellow and the catalytic domain in teal. The prolines within the N-terminal cap domain are depicted as violet
807 sticks. C) Superposition of EH_0 and its homologs: E53 (yellow, PDB code 7W8N), Est8 (violet, PDB code 4YPV),
808 PestE (raspberry, PDB code 3ZWQ) and EstA (slate, PDB code 5LK6). D) Superposition of subunits A and B showing
809 different conformations of loop α1-α2, with chain A in green and chain B in blue. Cap/catalytic domains follow
810 the color code described in B.

811

812 FIG 4. A) EH_0 homodimer showing the catalytic triad as sticks (violet). Both subunits are related by a twofold axis
813 that is perpendicular to the view shown and situates the two active sites on opposite faces of the dimer. B) A
814 magnified image of the dimeric interface that covers 722.9$Å^2$ (approximately 5.6% of the total surface), showing
815 hydrogen bonds (pink) and salt bridges (green). The Cap domain is colored yellow, whereas the catalytic domain
816 is shown in teal. C) Dimeric interface of the PestE homolog where the interactions are made by β8 and α12. D)

817 Dimeric interface of EH_0, where the interactions are made by α8, β8 and α9. Disposition of catalytic tunnels from
818 both subunits in PestE (E) and EH_0 (F).
819
820 FIG 5. A) A tunnel 16.8 deep giving access to the catalytic triad. B) Hydrogen bond network among the residues
821 making the catalytic triad of EH_0 (teal). Movement of loop β3-α3 in EH_0 (housing the oxoanion) with respect to
822 its homologs E53 complexed with (4-nitrophenyl)hexanoate (yellow), Est8 (violet), PestE (raspberry) and EstA
823 (slate). C) Hydrogen bond network of residues Glu226 and Tyr223 from α7. D) Hydrophobic patch where Trp218
824 is located. The EH_0 cap domain is shown in yellow and the catalytic domain in teal (C and D.)E) All possible
825 conformations of the region comprising α1-α2 shown by the ensemble refinement of molecule A. Color code
826 gives chain mobility, from low (blue) to high (red). The opposed scenarios of the region α1-α2, from an "open
827 conformation" (F, green) to a "closed conformation" (G, slate). The cap domain seen in the crystal structure is
828 shown in yellow. H) All conformers shown by the ensemble refinement of molecule B. I and J) Superimposition
829 of EH_0 onto E53 complexed with 4-nitrophenylhexanoate (yellow) and EH_{1AB1} in complex with a derivative of
830 methyl 4-nitrophenylhexylphosphonate (green), showing only the ligands. The catalytic triad of EH_0 is shown as
831 violet sticks, and residues Glu226 and Ile255 are shown as gray sticks. The EH_0 cap domain is shown in yellow and
832 the catalytic domain in teal. K) Active site cavity of EH_0 with acyl and alcohol moieties. Residues from the cap
833 domain are colored yellow, and residues from the catalytic domain are colored teal. The catalytic triad is shown
834 in violet.
835
836 FIG 6. A) Multiple sequence alignment of EH_0 and its homologs E53, Est8, PestE and EstA. Highlighted in boxes
837 are the conserved motif G-X-S-X-G (in blue), including the catalytic serine, and the D-P-X-X-D (in green), including
838 the catalytic aspartic acid. The prolines from loop α1-α2 (Pro21, Pro23 and Pro31) and the potential hinges (Pro46
839 and Pro47) are underlined in purple. The catalytic triad residues are shown with yellow triangles.
840
841 FIG 7. A) Superposition of EH_0 (teal), EH_{1AB1} (purple) and EH_3 (orange). Most differences are found in the cap
842 domain. Catalytic cavities of EH_{1AB1} (B), EH_3 (C) and EH_0 (D).

FIG 1.

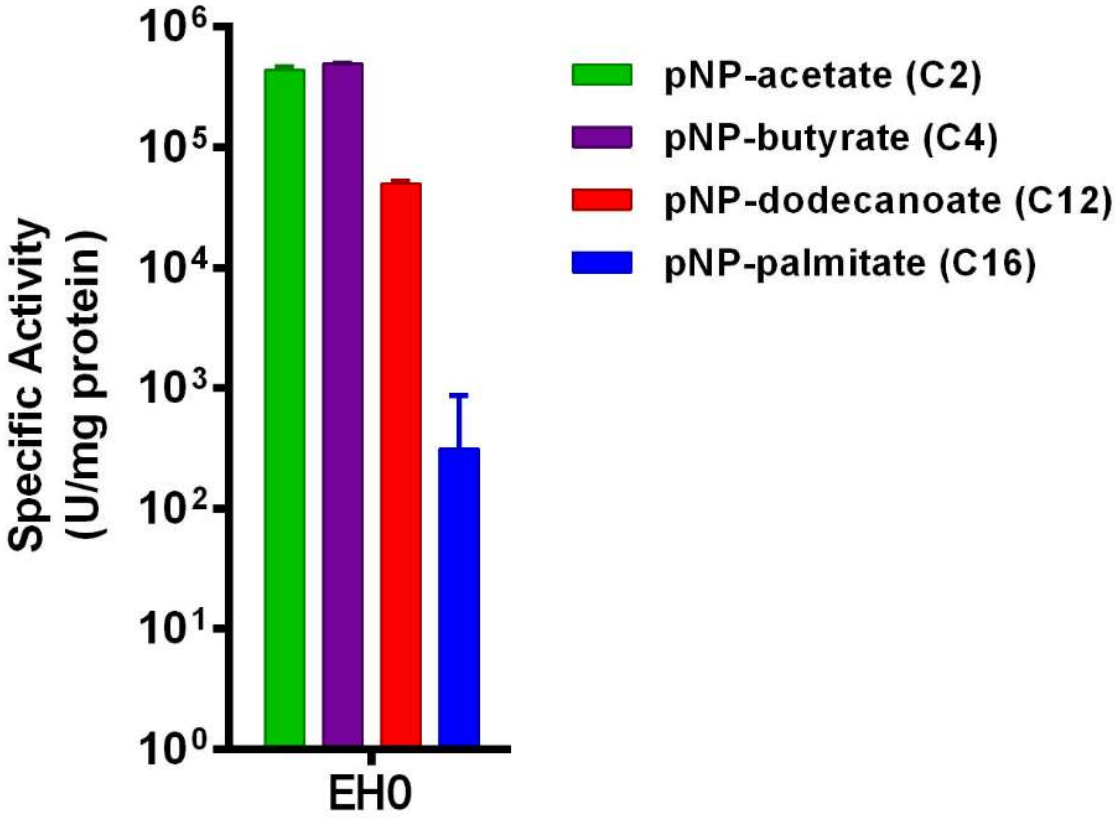

Specific Activity
(U/mg protein)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
EH0
pNP-acetate (C2)
pNP-butyrate (C4)
pNP-dodecanoate (C12)
pNP-palmitate (C16)

FIG 2.

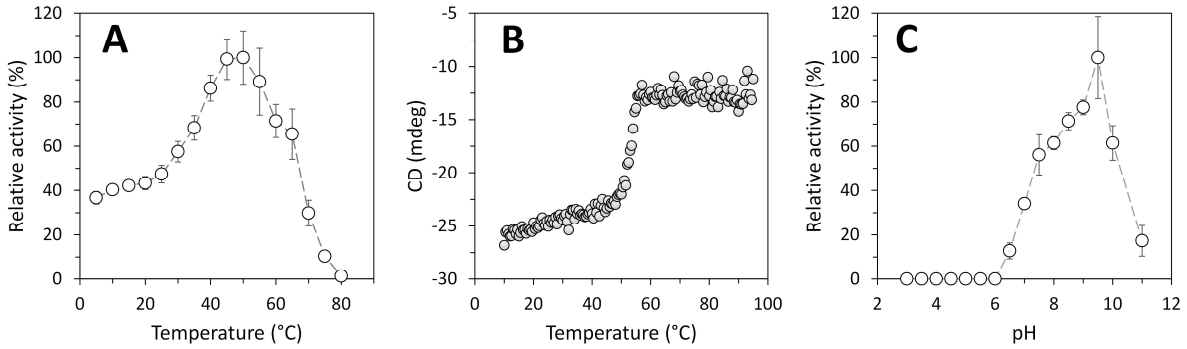

A
Relative activity (%)
Temperature (°C)
B
CD (mdeg)
Temperature (°C)
C
Relative activity (%)
pH

FIG 3.

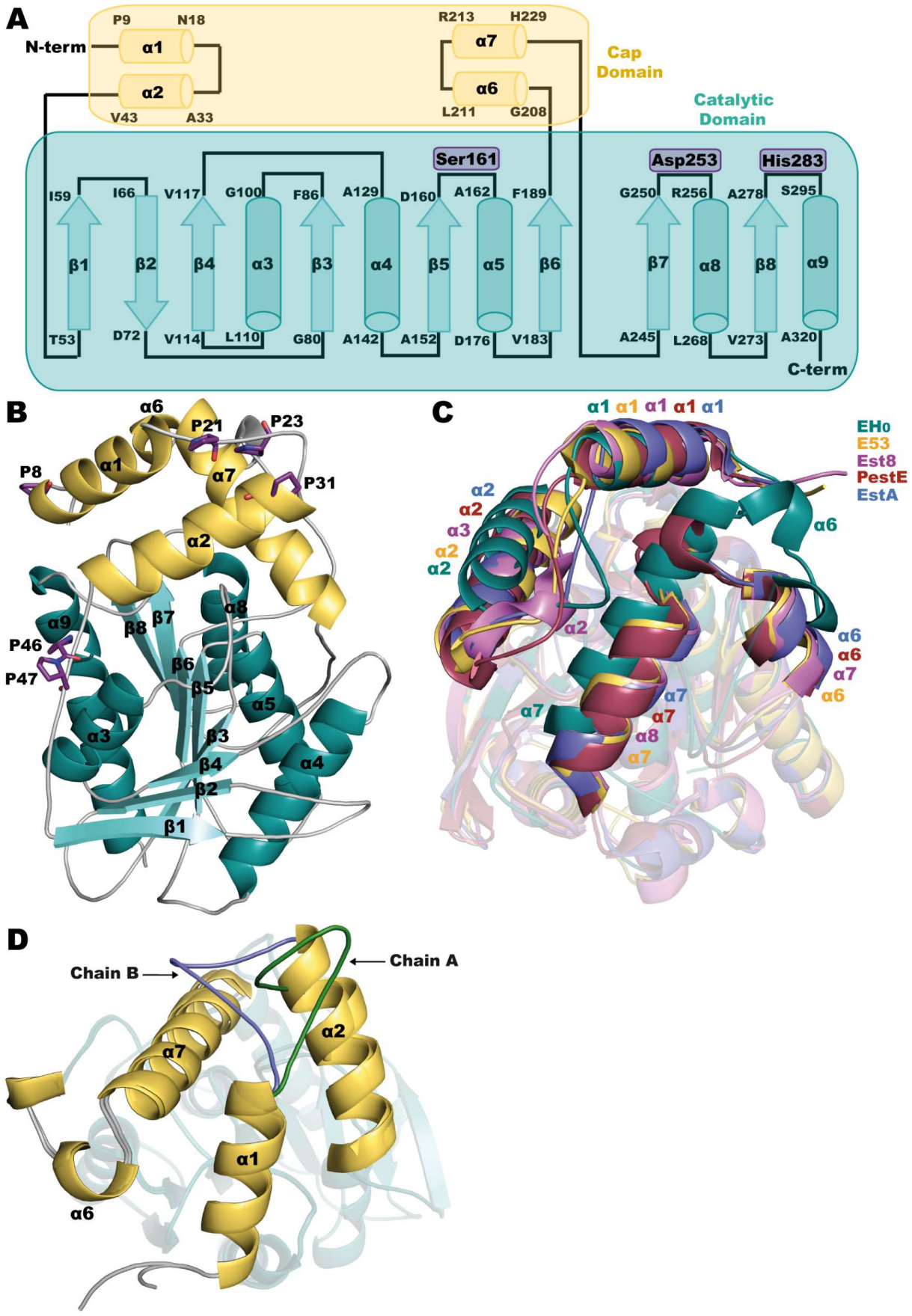

A
N-term
P9
N18
α1
α2
V43
A33
R213
H229
α7
α6
L211
G208
Cap Domain
Catalytic Domain
Ser161
Asp253
His283
I59
I66
V117
G100
F86
A129
D160
A162
F189
G250
R256
A278
S295
β1
β2
β4
α3
β3
α4
β5
α5
β6
β7
α8
β8
α9
T53
D72
V114
L110
G80
A142
A152
D176
V183
A245
L268
V273
A320
C-term
B
α6
P21
P23
P8
α1
α7
P31
α2
α9
β8
β7
α8
P46
P47
β6
β5
α5
α3
β3
α4
β4
β2
β1
C
α1 α1 α1 α1 α1
EHo
E53
Est8
PestE
EstA
α2
α2
α3
α2
α2
α6
α2
α6
α6
α7
α6
α7
α7
α7
α8
α7
D
Chain B
Chain A
α2
α7
α1
α6

FIG 4.

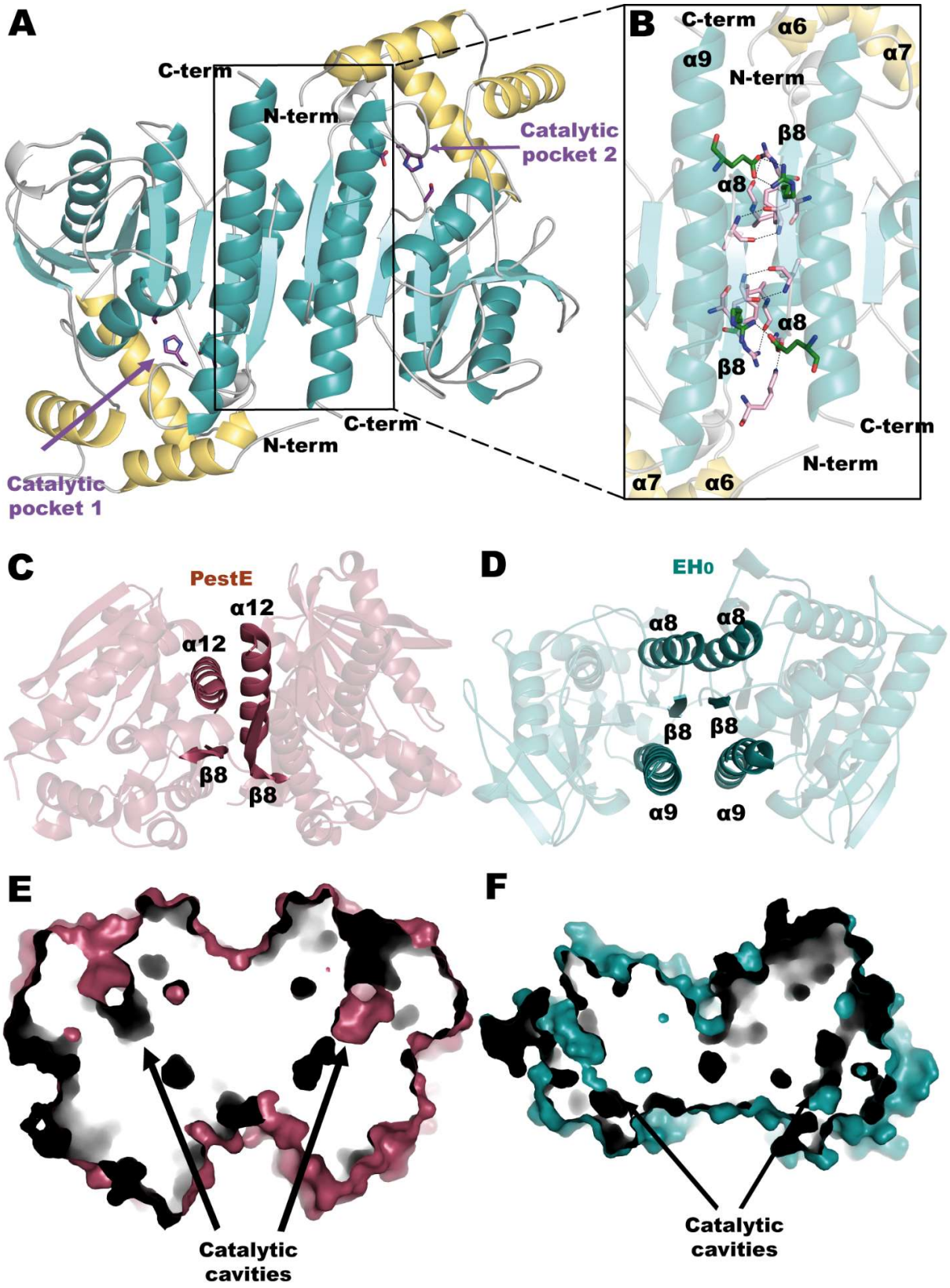

A
C-term
N-term
Catalytic pocket 2
C-term
N-term
Catalytic pocket 1
B
C-term
α6
α9
α7
N-term
β8
α8
α8
β8
C-term
N-term
α7
α6
C
PestE
α12
α12
β8
β8
D
EH0
α8
α8
β8
β8
α9
α9
E
Catalytic cavities
F
Catalytic cavities

FIG 5.

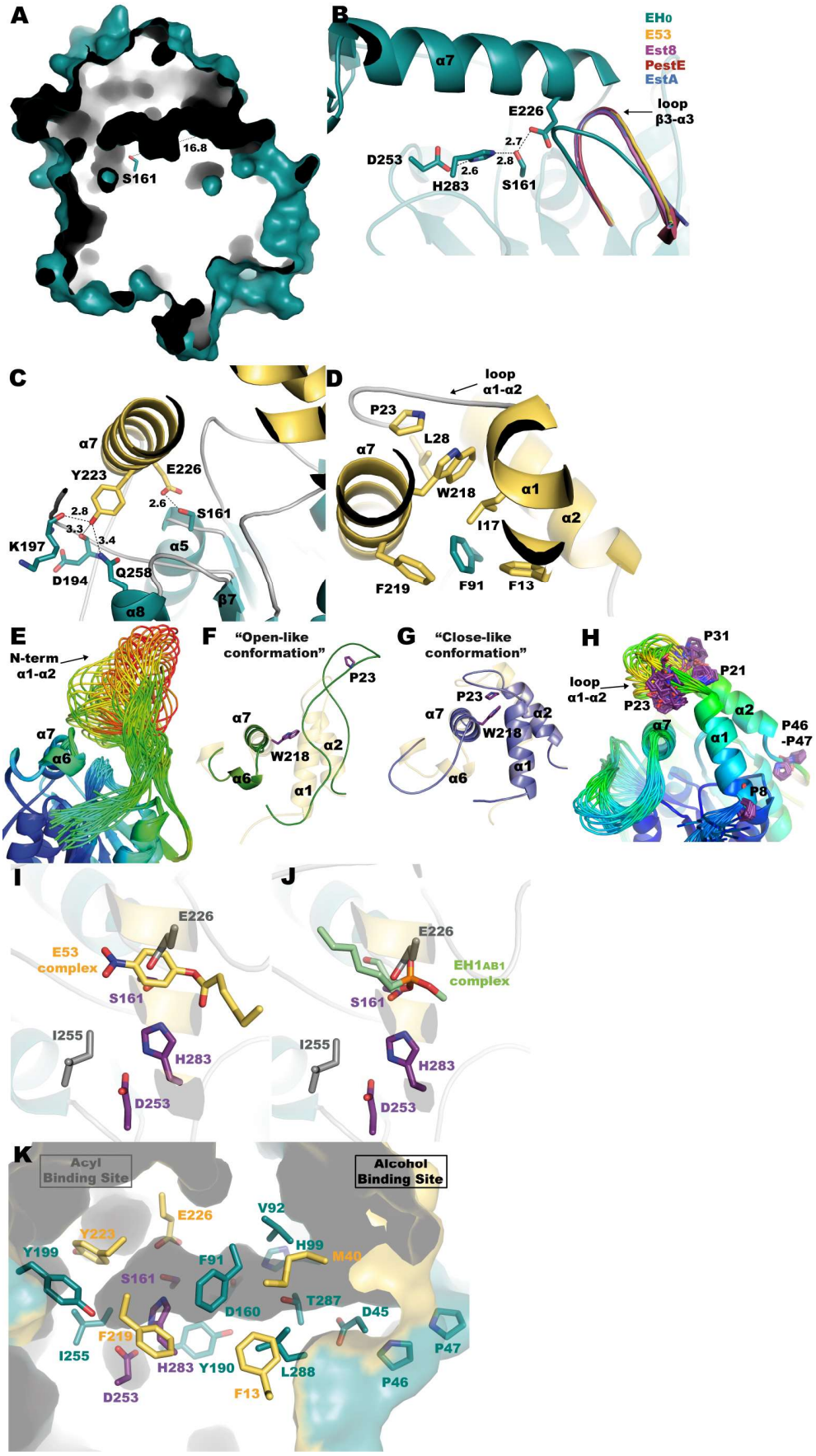
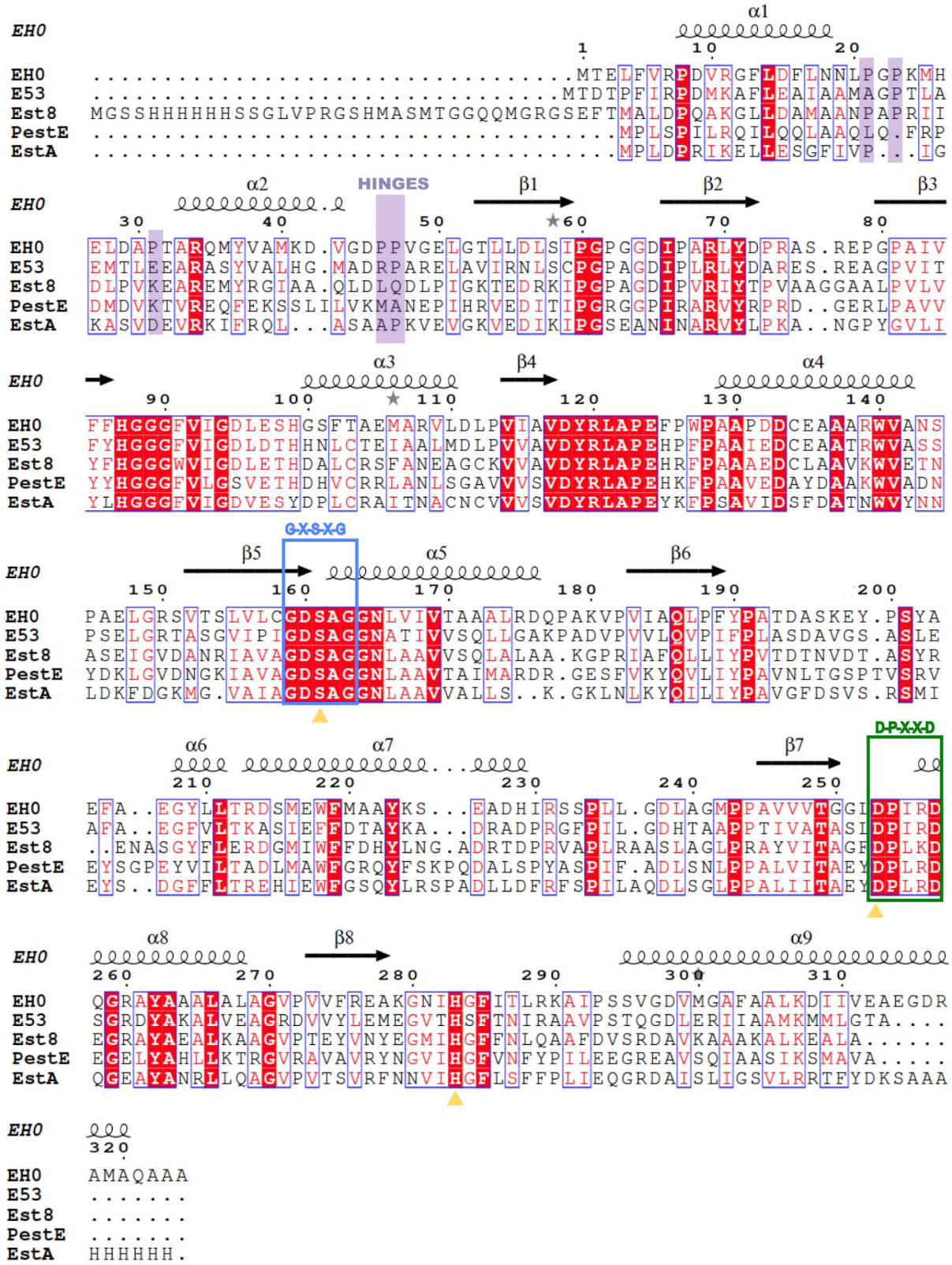

A
16.8
S161
B
EH0
E53
Est8
PestE
EstA
α7
E226
loop
β3-α3
2.7
D253
2.6
2.8
H283
S161
C
α7
Y223
E226
2.8
2.6
S161
3.3
3.4
K197
α5
D194
Q258
α8
β7
D
loop
α1-α2
P23
L28
α7
W218
α1
I17
α2
F219
F91
F13
E
N-term
α1-α2
α7
α6
F
"Open-like
conformation"
P23
α7
W218
α2
α6
α1
G
"Close-like
conformation"
P23
α7
α2
W218
α1
α6
H
P31
P21
loop
α1-α2
P23
α2
α7
α1
P46
-P47
P8
I
E226
E53
complex
S161
I255
H283
D253
J
E226
EH1AB1
complex
S161
I255
H283
D253
K
Acyl
Binding Site
Alcohol
Binding Site
E226
V92
Y223
H99
Y199
F91
M40
S161
T287
D160
D45
F219
P47
I255
H283
Y190
L288
P46
D253
F13

FIG 6.


EH0
α1
1 10 20
EH0 .....MTELFVRPDVRGFLDFLNNLPGPKMH
E53 .....MTDTPFIRPDMKAFLEAIAAMAGPTLA
Est8 MGSSHHHHHHSSGLVPRGSHMASMTGGQQMGRGSEFTMALDPQAKGLLDAMAANPAPRII
PestE .....MPLSPILRQILQQLAAQLQ.FRP
EstA .....MPLDPRIKELLESGFIVP...IG
α2
HINGES
β1
β2
β3
30 40 50 60 70 80
EH0 ELDAPTARQMYVAMKD.VGDPPVGELGTLLDLSIPGPGGDIPARLYDPRAS.REPGPAIV
E53 EMTLEEARASYVALHG.MADRPARELAVIRNLSCPGPAGDIPLRLYDARES.REAGPVIT
Est8 DLPVKEAREMYRGIAA.QLDLQDLPIGKTEDRKIPGPAGDIPVRIYTPVAAGGAALPVLV
PestE DMDVKTVREQFEKSSLILVKMANEPIHRVEDITIPGRGGPIRARVYRPRD..GERLPAVV
EstA KASVDEVRKIFRQL...ASAAPKVEVGKVEDIKIPGSEANINARVYLPKA..NGPYGVLI
α3
β4
α4
90 100 110 120 130 140
EH0 FFHGGGFVIGDLESHGSFTAEMARVLDLPVIAVDYRLAPEFPWPAAPDDCEAAARWVANS
E53 FYHGGGFVIGDLDTHHNLCTEIAALMDLPVVAVDYRLAPEHPFPAAIEDCEAATRWVASS
Est8 YFHGGGWVIGDLETHDALCRSFANEAGCKVVAVDYRLAPEHRFPAAAEDCLAAVKWVETN
PestE YYHGGGFVLGSVETHDHVCRRLANLSGAVVVSVDYRLAPEHKFPAAVEDAYDAAKWVADN
EstA YLHGGGFVIGDVESYDPLCRAITNACNCVVVSVDYRLAPEYKFPSAVIDSFDATNWVYNN
G-X-S-X-G
β5
α5
β6
150 160 170 180 190 200
EH0 PAELGRSVTSLVLCGDSAGGNLVIVTAAALRDQPAKVPVIAQLPFYPATDASKEY.PSYA
E53 PSELGRTASGVIPIGDSAGGNATIVVSQLLGAKPADVPVVLQVPIFPLASDAVGS.ASLE
Est8 ASEIGVDANRIAVAGDSAGGNLAAVVSQLALAA.KGPRIAFQLLIYPVTDTNVDT.ASYR
PestE YDKLGVDNGKIAVAGDSAGGNLAAVTAIMARDR.GESFVKYQVLIYPAVNLTGSPTVSRV
EstA LDKFDGKMG.VAIAGDSAGGNLAAVVALLS..K.GKLNLKYQILIYPAVGFDSVS.RSMI
α6
α7
β7
D-P-X-X-D
210 220 230 240 250
EH0 EFA..EGYLLTRDSMEWFMAAYKS...EADHIRSSPLL.GDLAGMPPAVVVTGGIDPIRD
E53 AFA..EGFVLTKASIEFFDTAYKA...DRADPRGFPIL.GDHTAAPPTIVATASIDPIRD
Est8 ..ENASGYFLERDGMIWFFDHYLNG.ADRTDPRVAPLRAASLAGLPRAYVITAGFDPLKD
PestE EYSGPEYVILTADLMAWFGRQYFSKPQDALSPYASPIF.ADLSNLPPALVITAEYDPLRD
EstA EYS..DGFFLTREHIEWFGSQYLRSPADLLDFRFSPILAQDLSGLPPALIITAEYDPLRD
α8
β8
α9
260 270 280 290 300 310
EH0 QGRAYAAALALAGVPVVFREAKGNIHGFITLRKAIPSSVGDVMGAFAALKDIIVEAEGDR
E53 SGRDYAKALVEAGRDVVYLEMEGVTHSFTNIRAAVPSTQGDLERIIAAMKMMLGTA....
Est8 EGRAYAEALKAAGVPTEYVNYEGMIHGFFNLQAAFDVSRDAVKAAAKALKEALA.....
PestE EGELYAHLLKTRGVRAVAVRYNGVIHGFVNFYPILEEGREAVSQIAASIKSMAVA.....
EstA QGEAYANRLLQAGVPVTSVRFNNVIHGFLSFFPLIEQGRDAISLIGSVLRRTFYDKSAAA
EH0
320
EH0 AMAQAAA
E53 .....
Est8 .....
PestE .....
EstA HHHHHH.

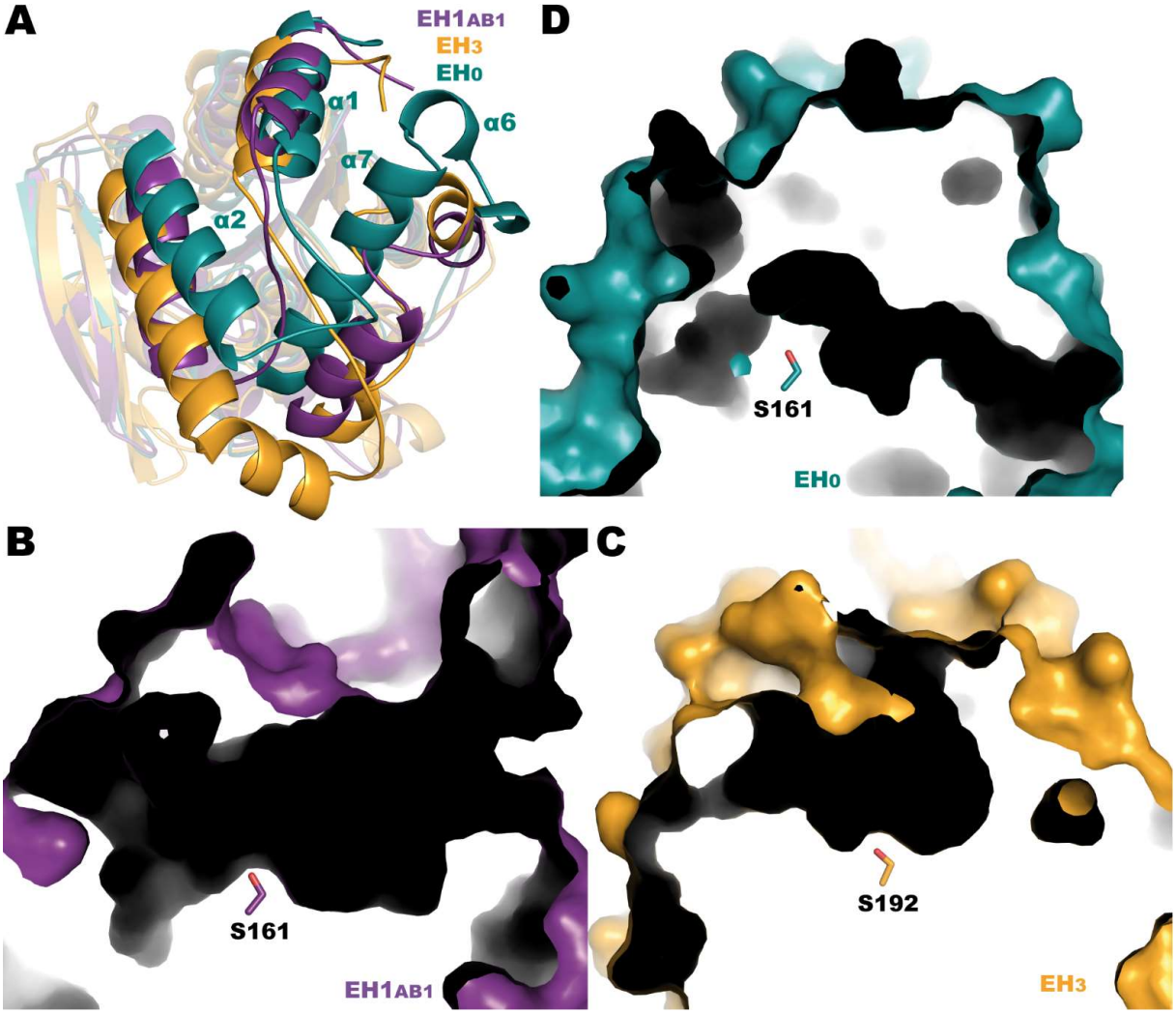



FIG 7.