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(54) **EVOLUTION OF BT TOXINS**

(71) Applicants: **President and Fellows of Harvard College**, Cambridge, MA (US); **Monsanto Company**, St. Louis, MO (US)

(72) Inventors: **David R. Liu**, Cambridge, MA (US); **Ahmed Hussein Badran**, Cambridge, MA (US); **Victor Guzov**, Cambridge, MA (US); **Tom Malvar**, North Stonington, CT (US); **Prashanth Vishwanath**, Arlington, MA (US); **Jeff Nageotte**, Billerica, MA (US); **Qing Huai**, Winchester, MA (US); **Melissa Kemp**, Medford, MA (US)

(73) Assignees: **President and Fellows of Harvard College**, Cambridge, MA (US); **Monsanto Company**, St. Louis, MO (US)

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(60) Provisional application No. 62/305,497, filed on Mar. 8, 2016, provisional application No. 62/196,253, filed on Jul. 23, 2015.

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C12N 15/10 (2006.01)
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CPC **C07K 14/325** (2013.01); **A01N 63/50** (2020.01); **C12N 15/1058** (2013.01); **C12N 15/8286** (2013.01)

(57) **ABSTRACT**

The disclosure provides amino acid sequence variants of *Bacillus thuringiensis* (Bt) toxins and methods of producing the same. Some aspects of this disclosure provide methods for generating Bt toxin variants by continuous directed evolution. Some aspects of this disclosure provide compositions and methods for pest control using the disclosed variant Bt toxins.

Specification includes a Sequence Listing.

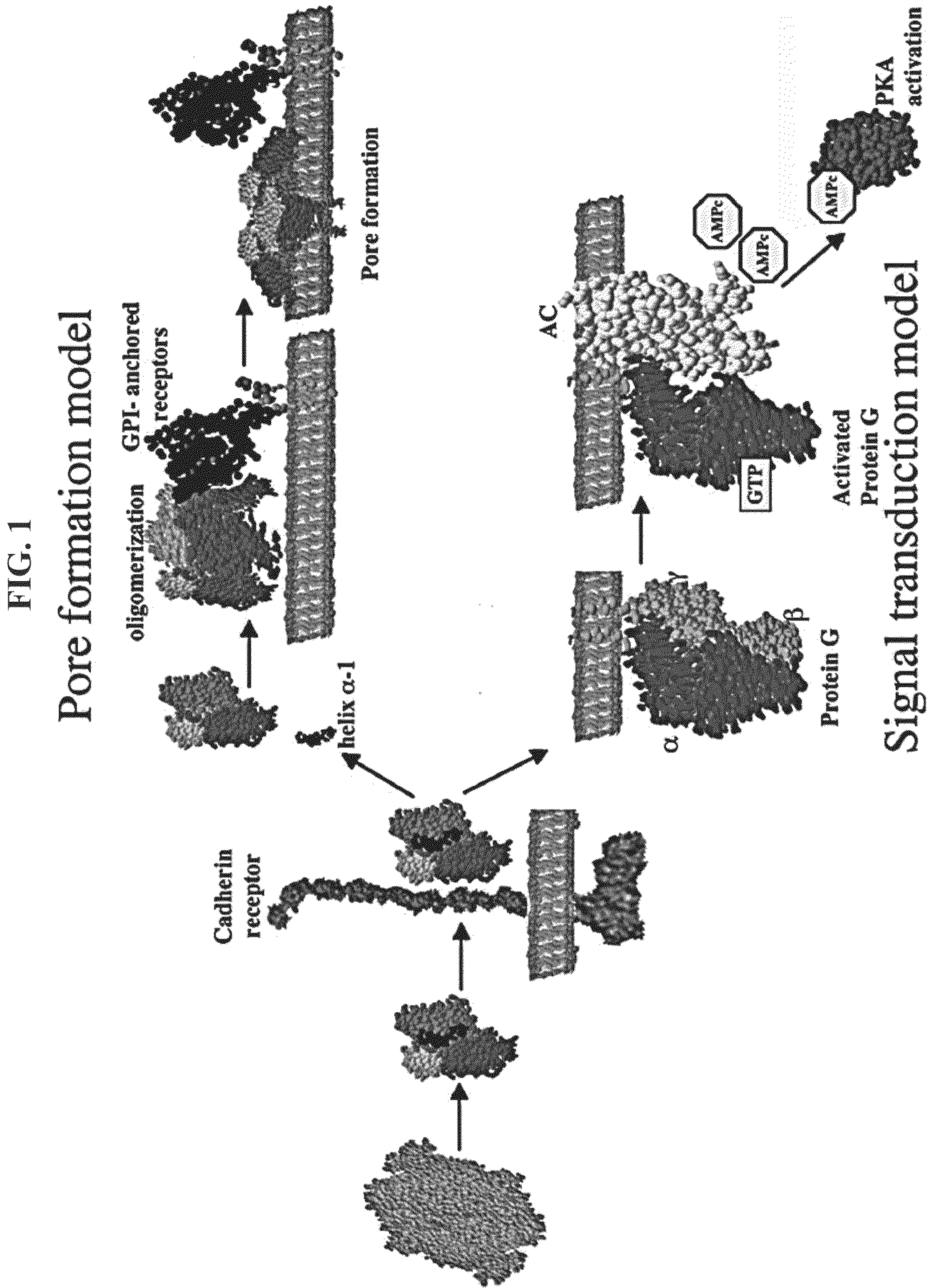
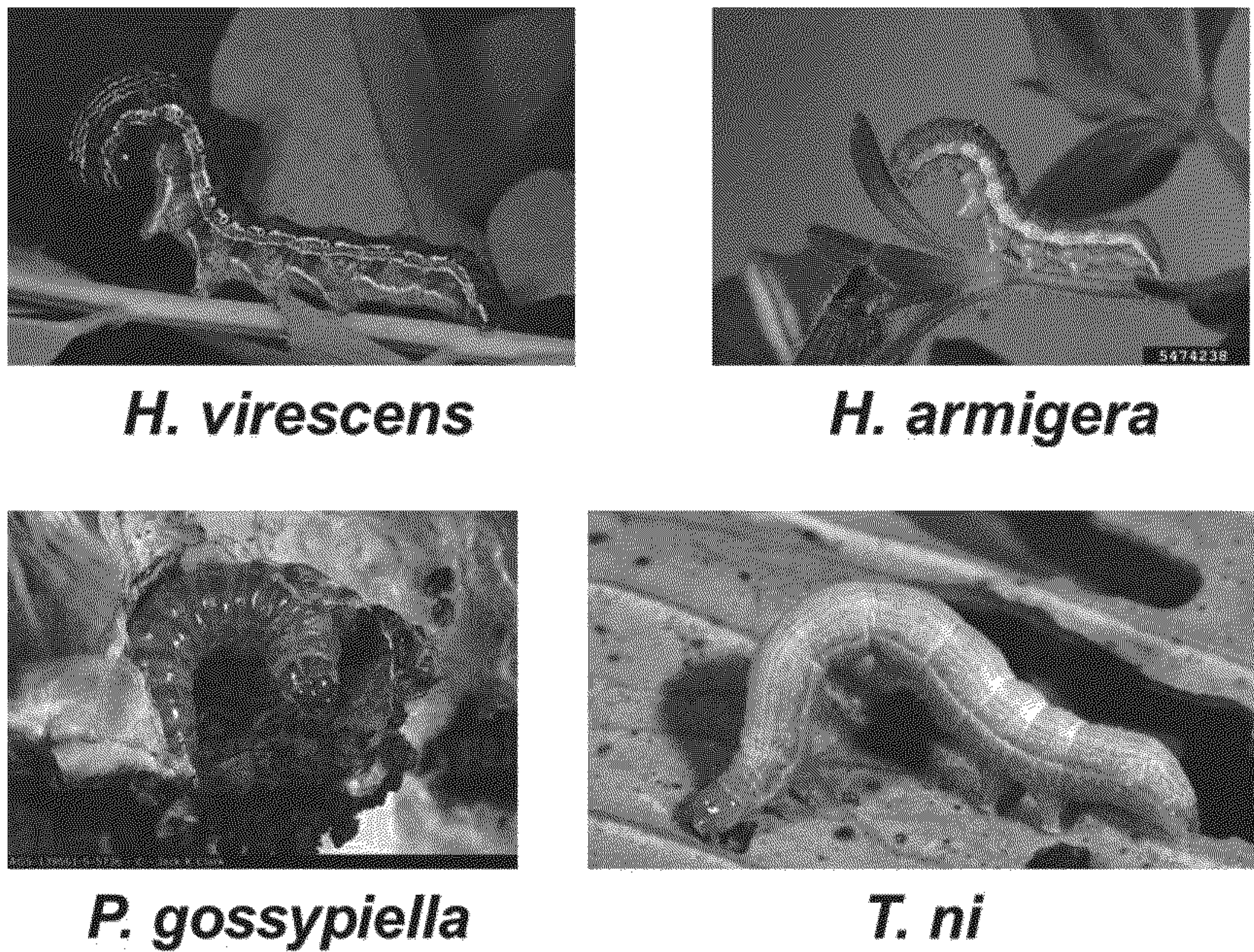


FIG. 2A



H. virescens	TGVLTLNFQPTASMHGMFEF
H. armigera	TGVLSLNFQPTAAMHGMFEF
P. gossypiella	TGVLILRIQPTASMQGMFEF
T. ni	SGVLSLNMNPLDTMVGMFEF
TBR3	SGVLSLNFNPSATMVGMFEF

FIG. 2B

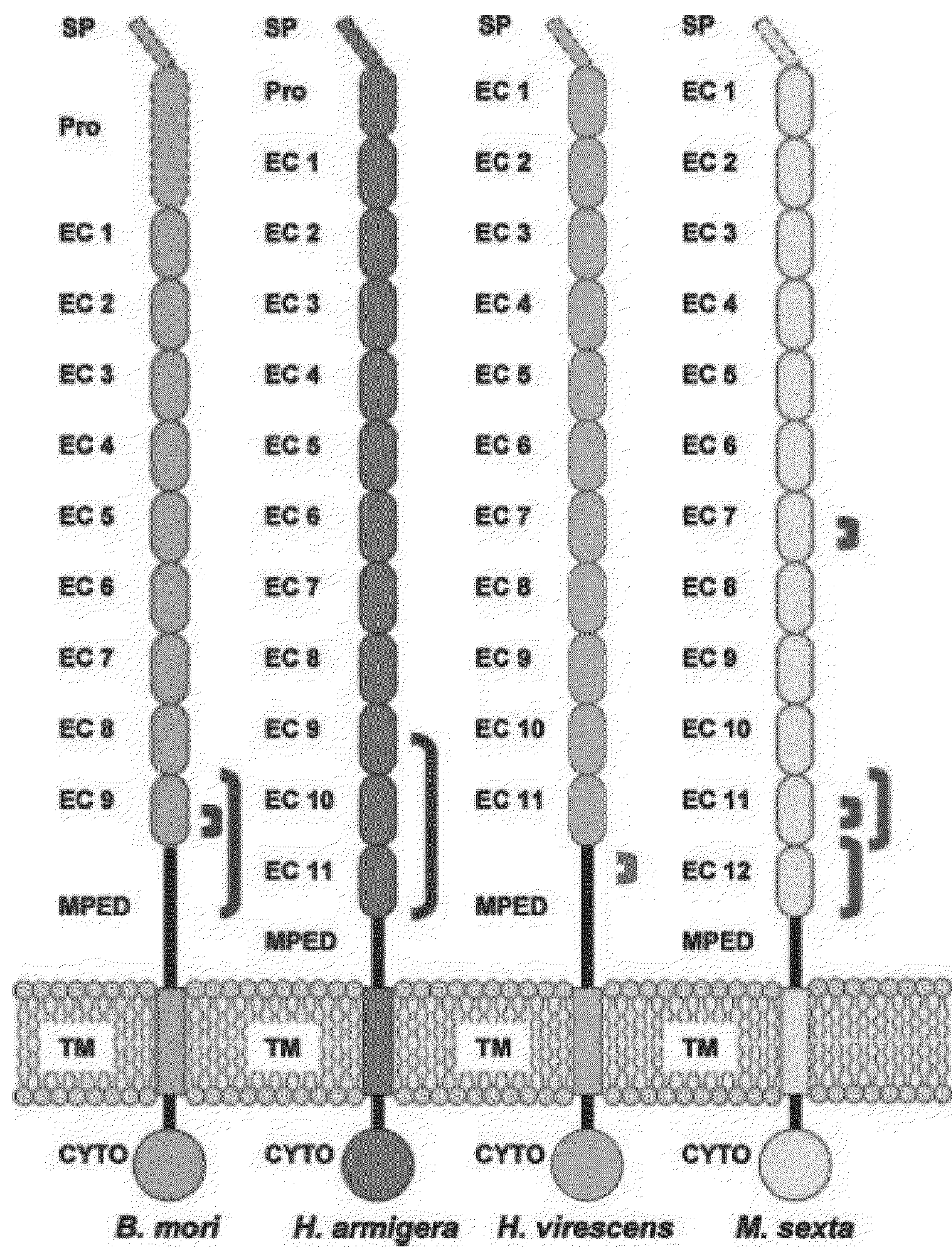
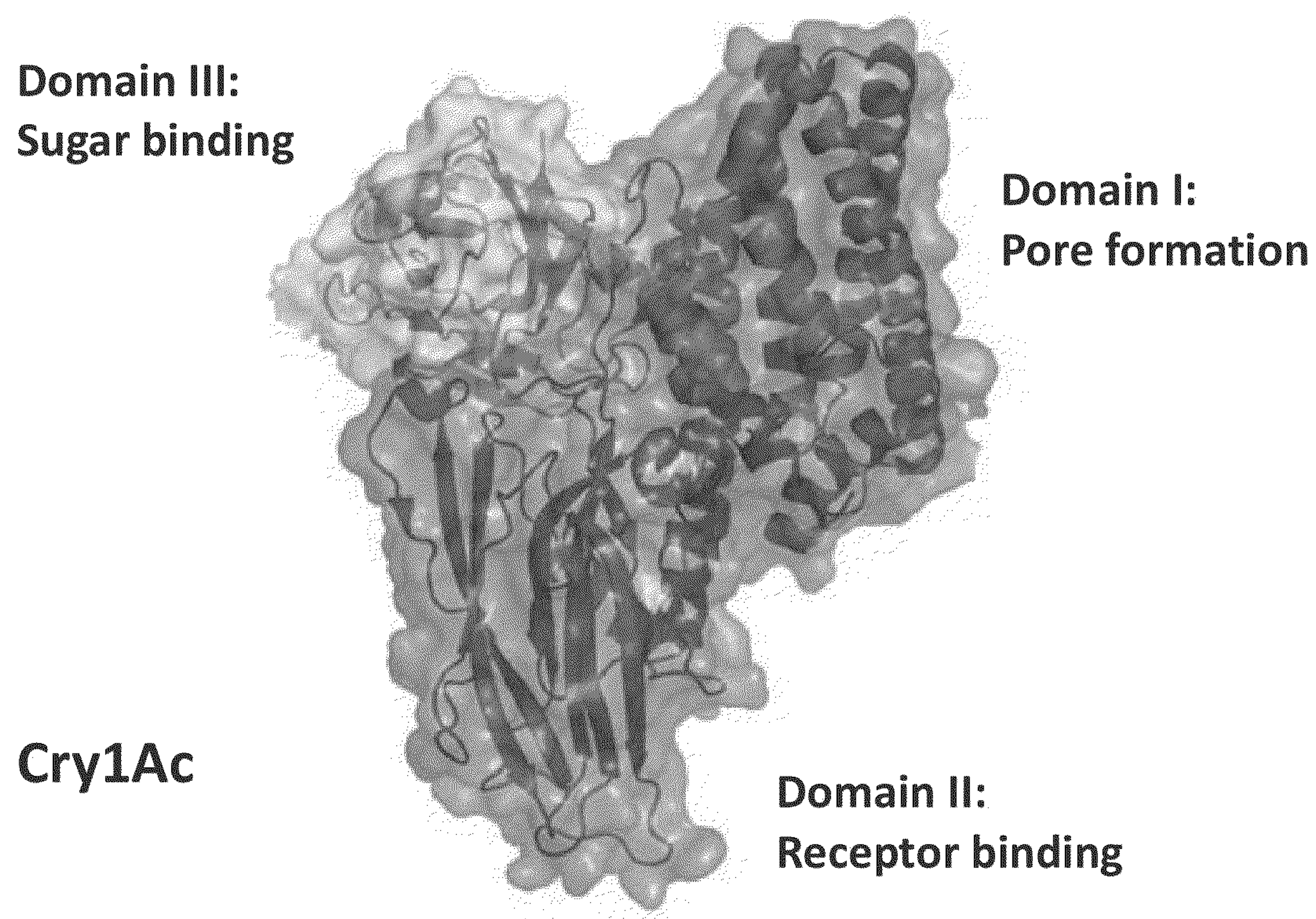


FIG. 2C



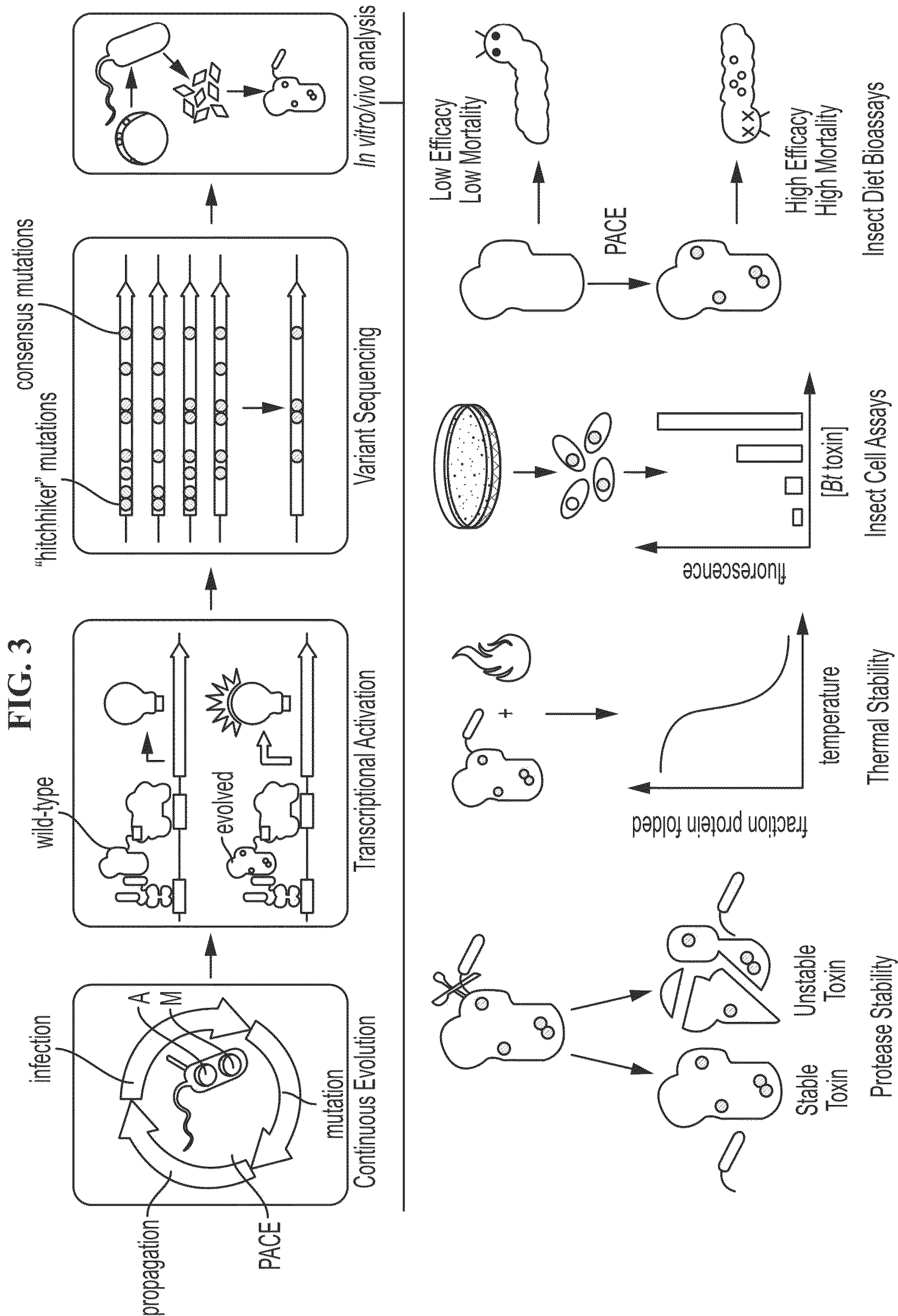


FIG. 4A

Round 1: low stringency/moderate mutagenesis

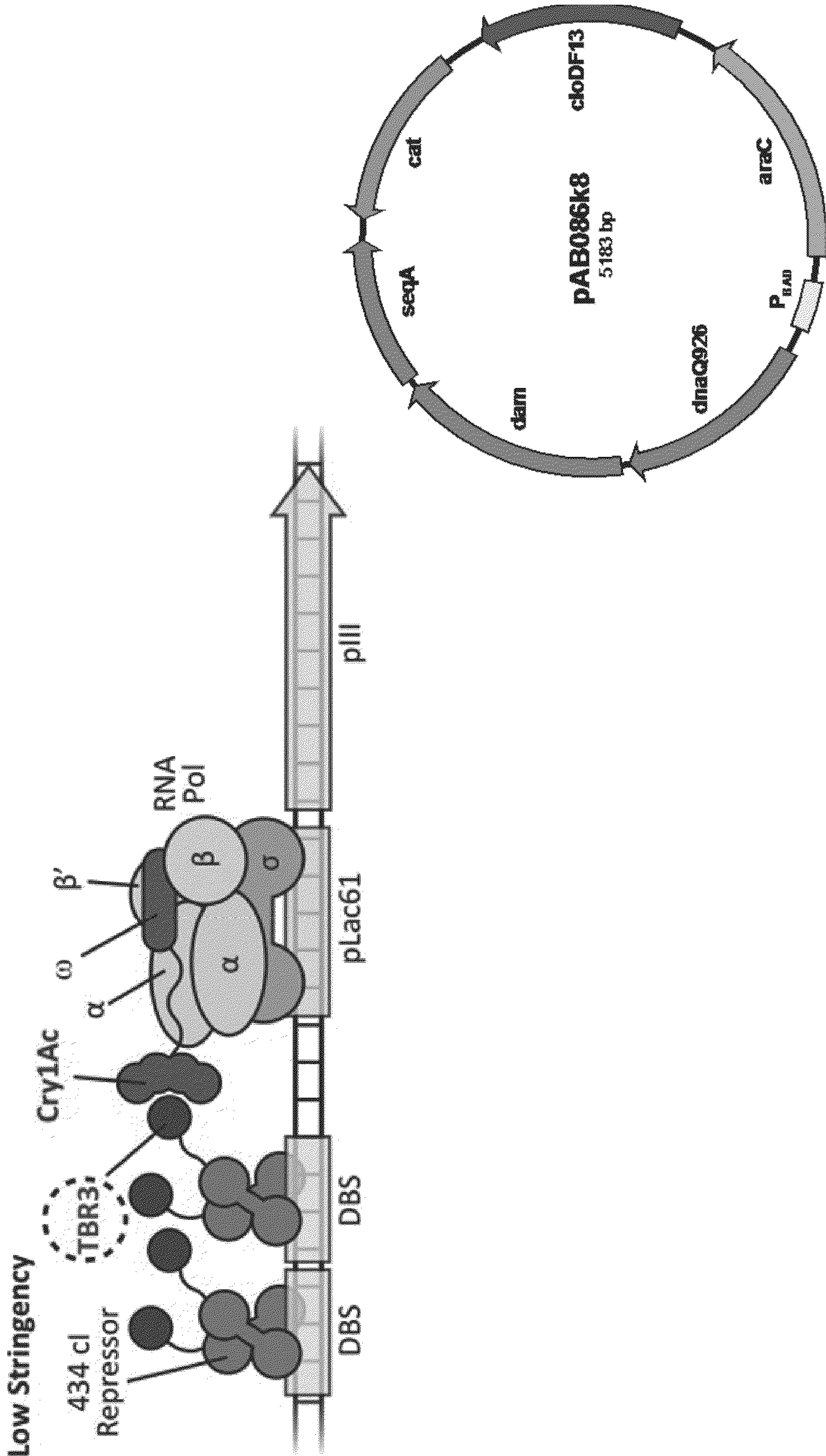


FIG. 4B

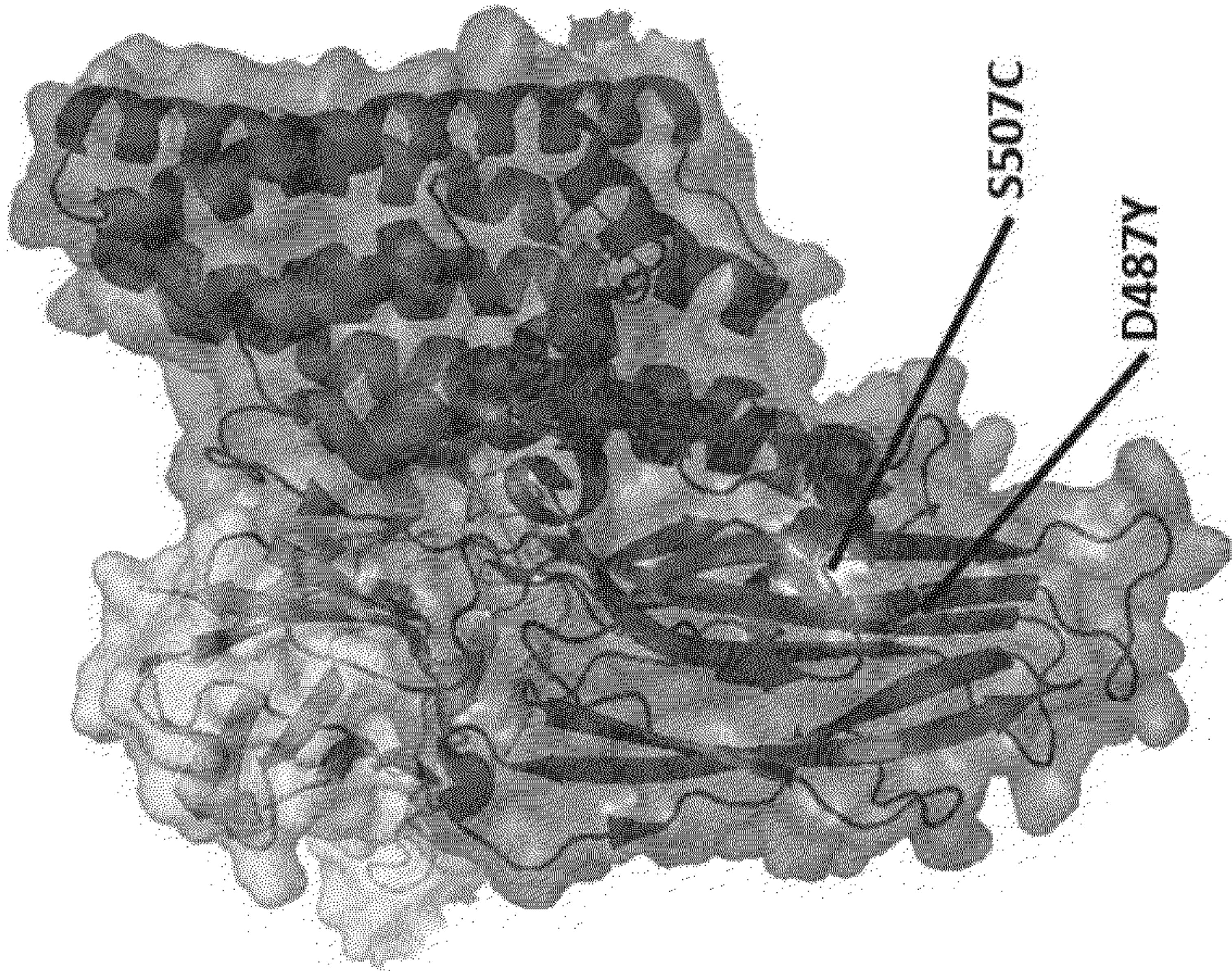
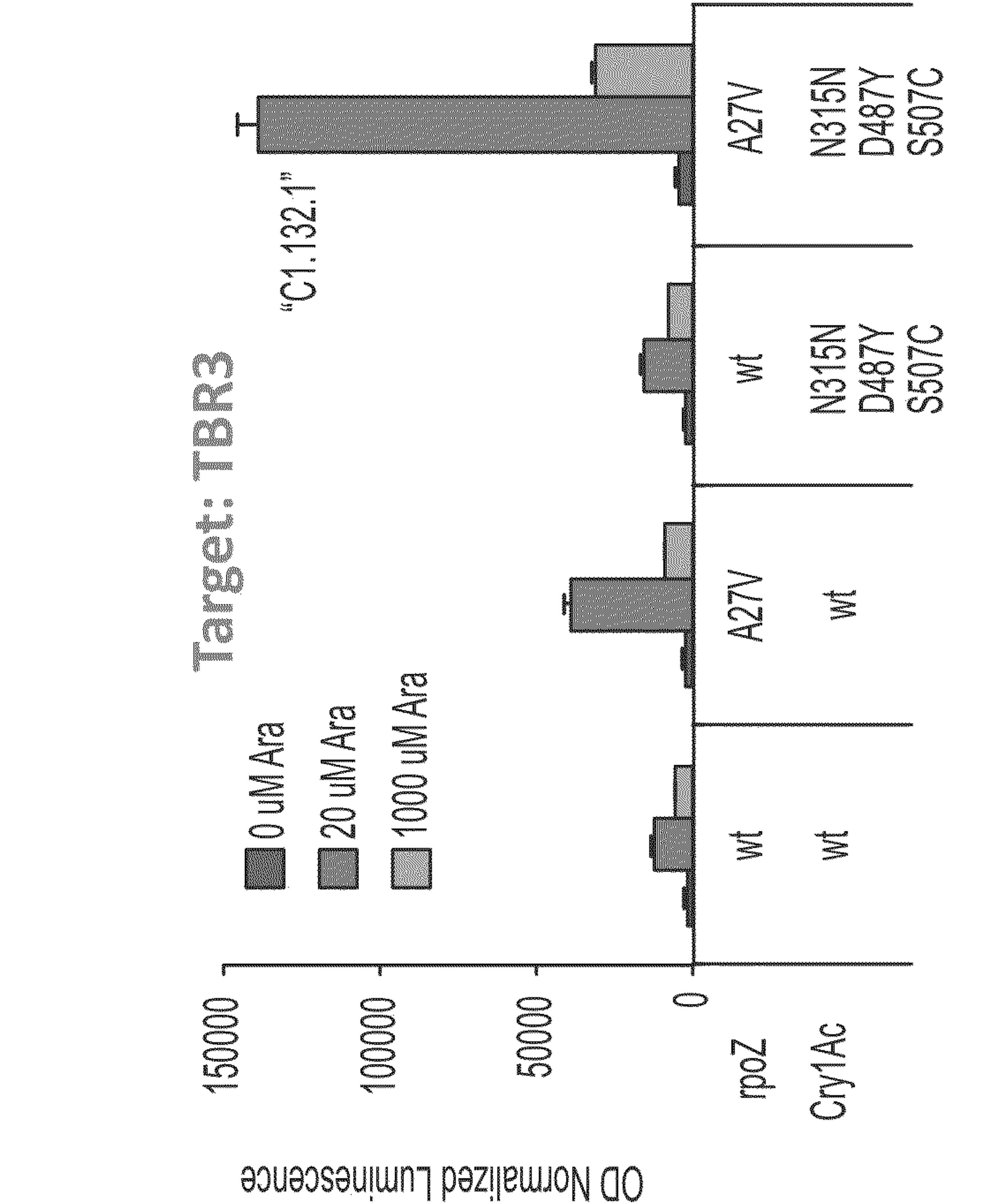


FIG. 5A

Round 2: intermediate stringency/moderate mutagenesis

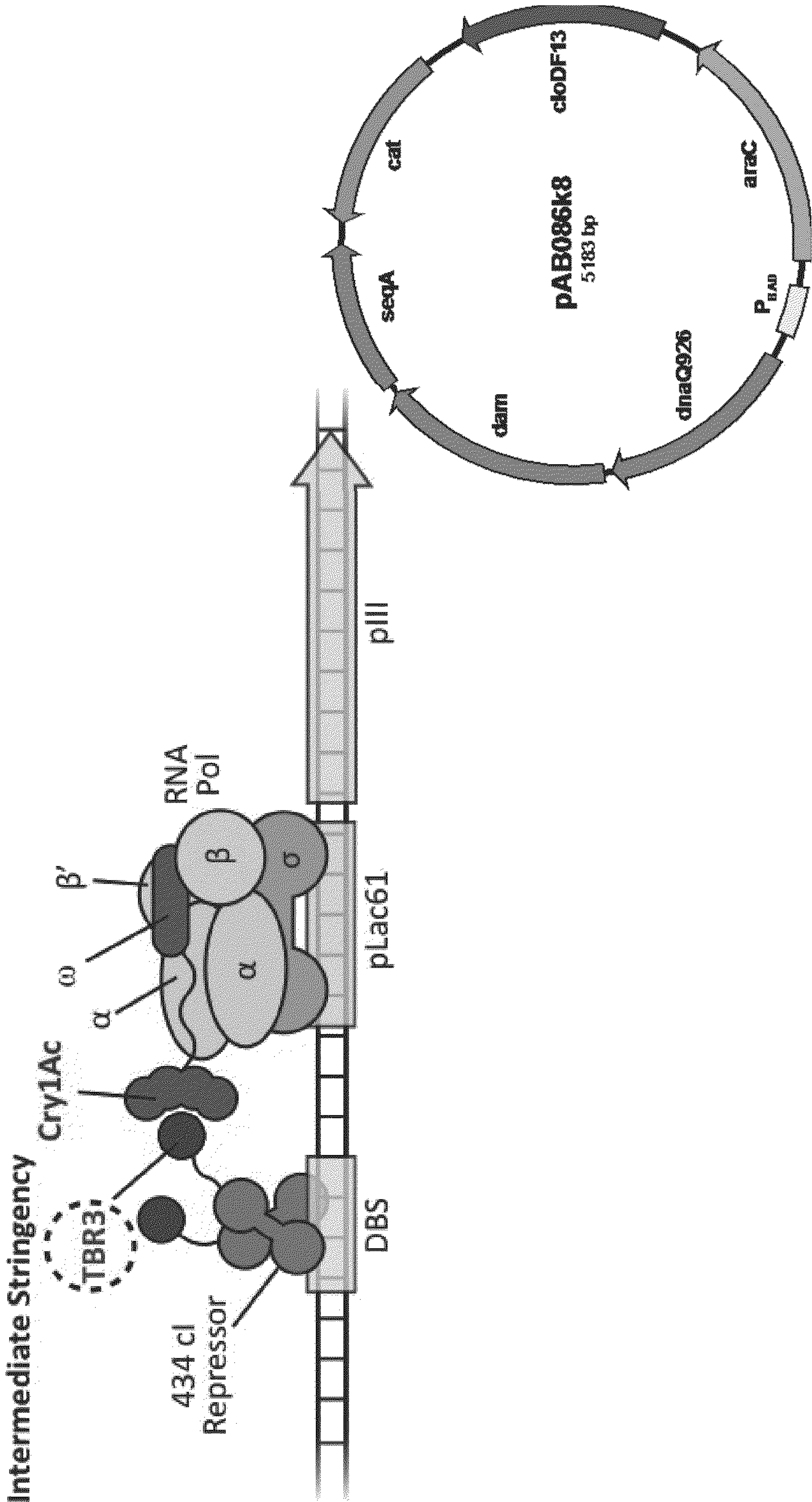
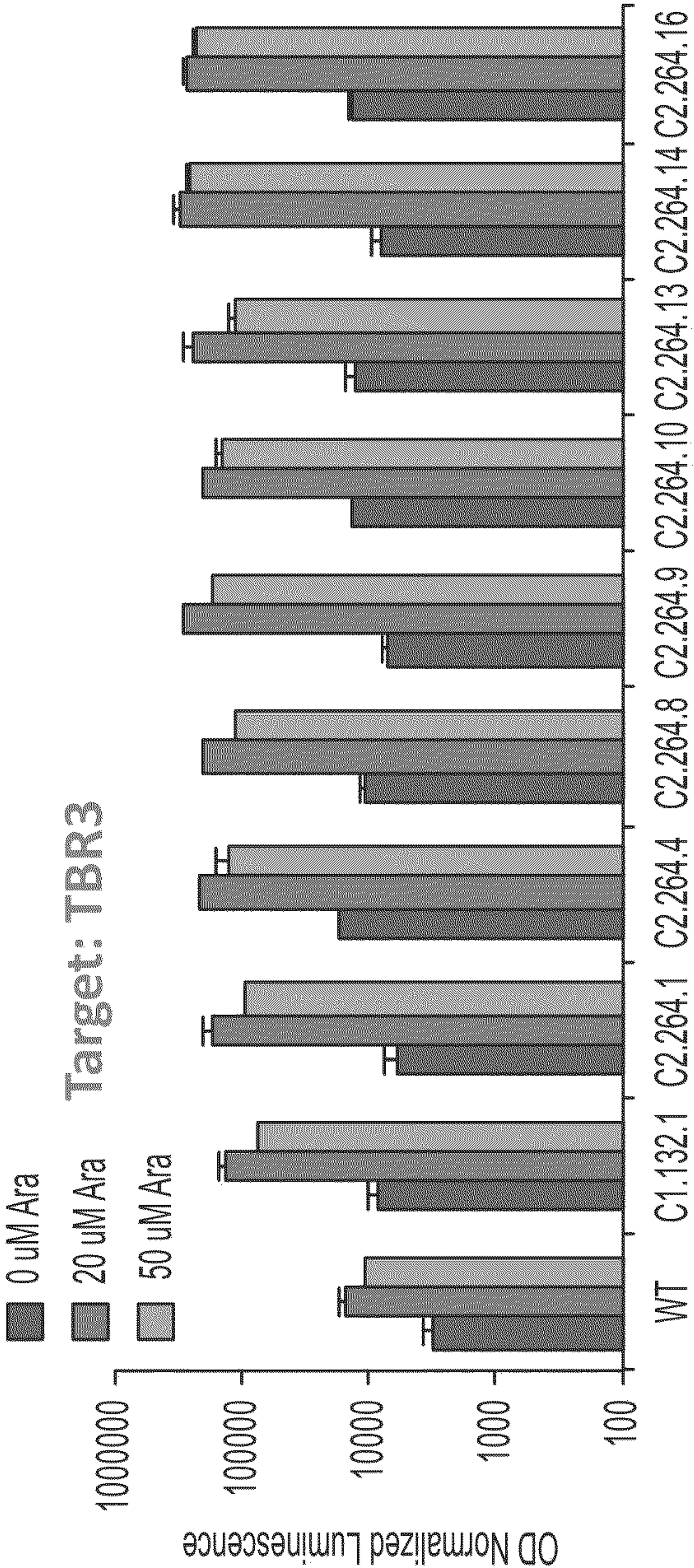


FIG. 5B



Round 3: intermediate stringency/high mutagenesis

FIG. 6A

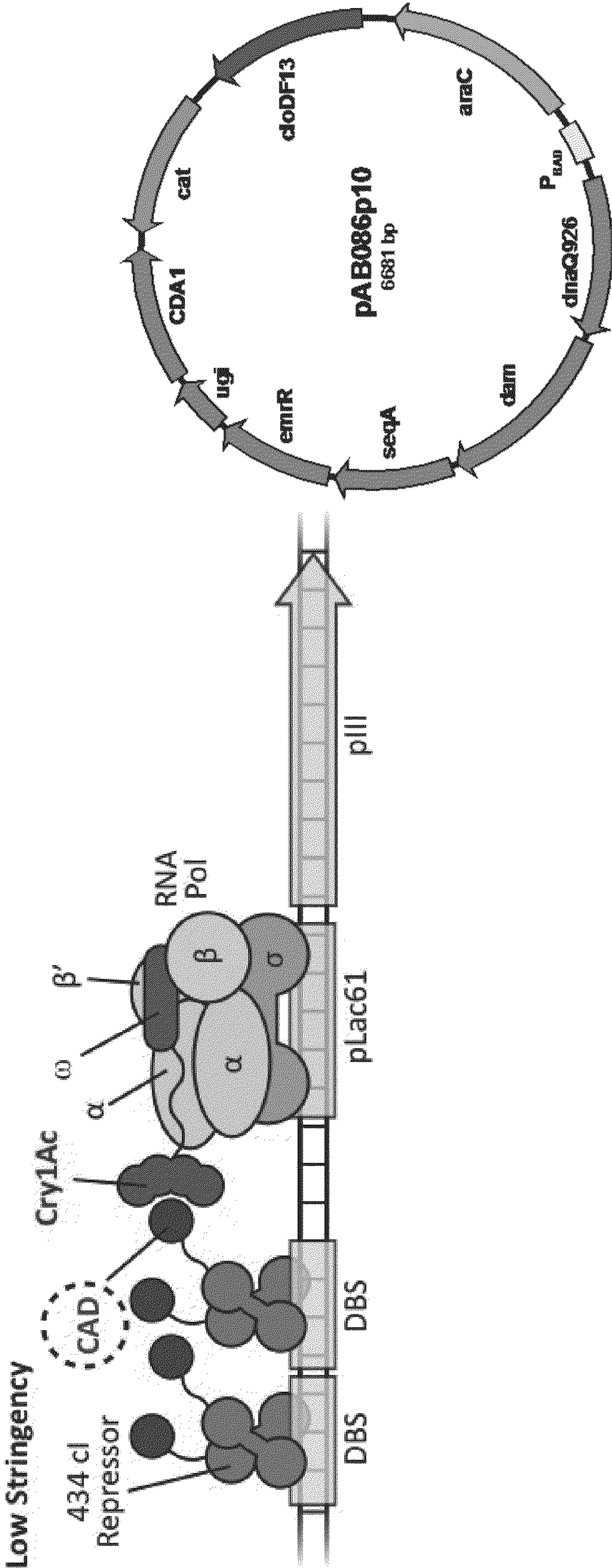


FIG. 6B

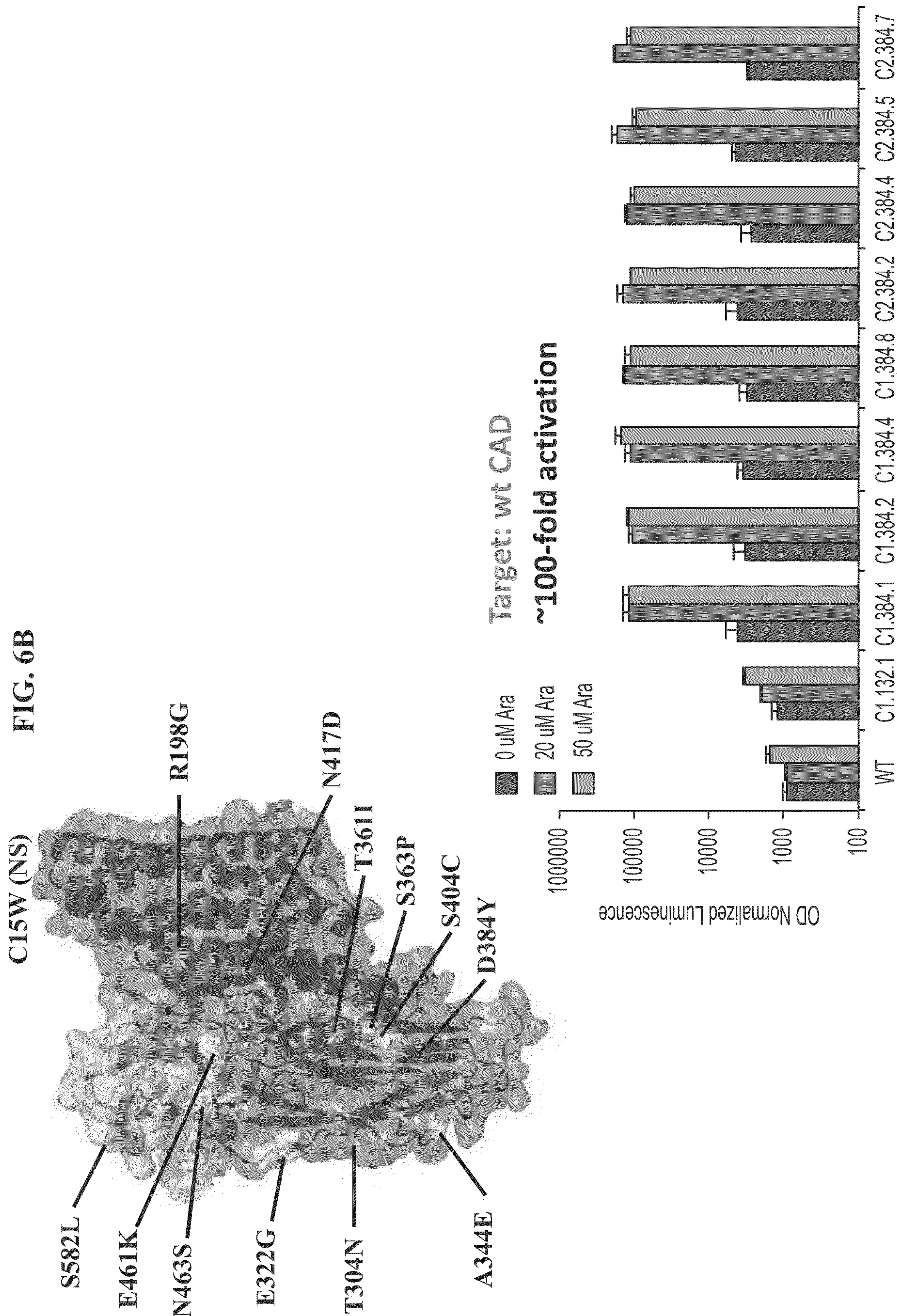


FIG. 7A

Round 4: high stringency/high mutagenesis

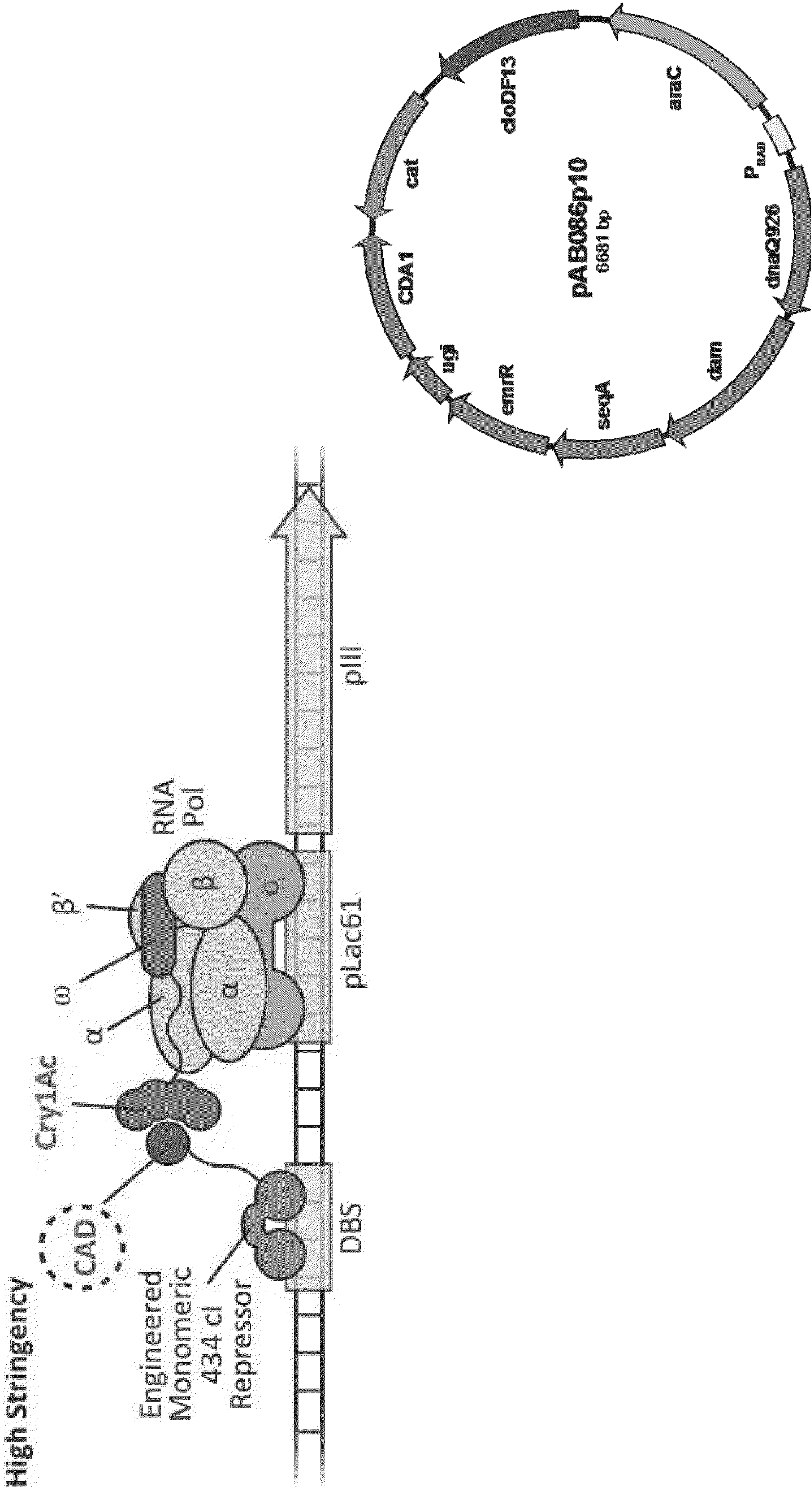


FIG. 7B

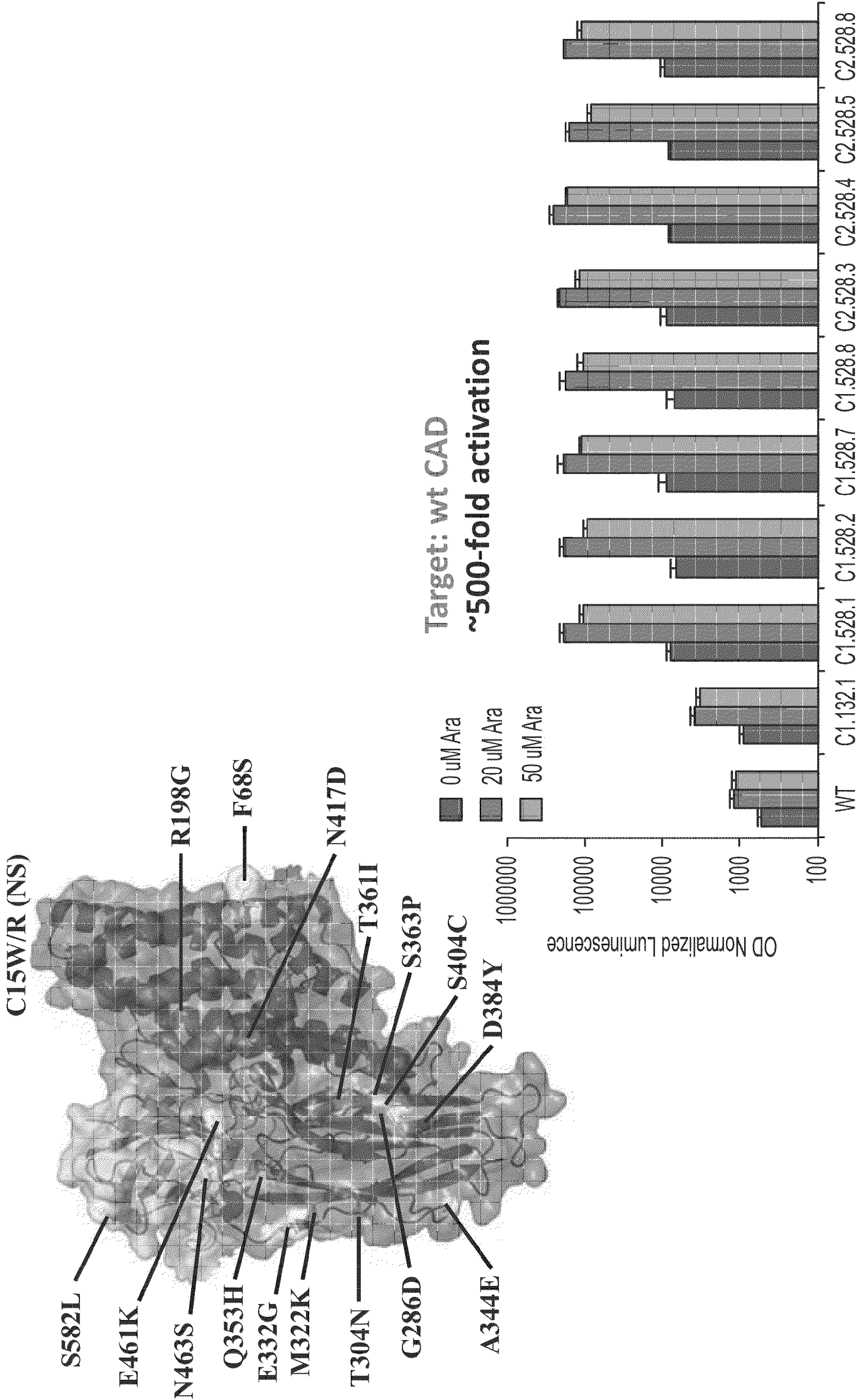


FIG. 8A

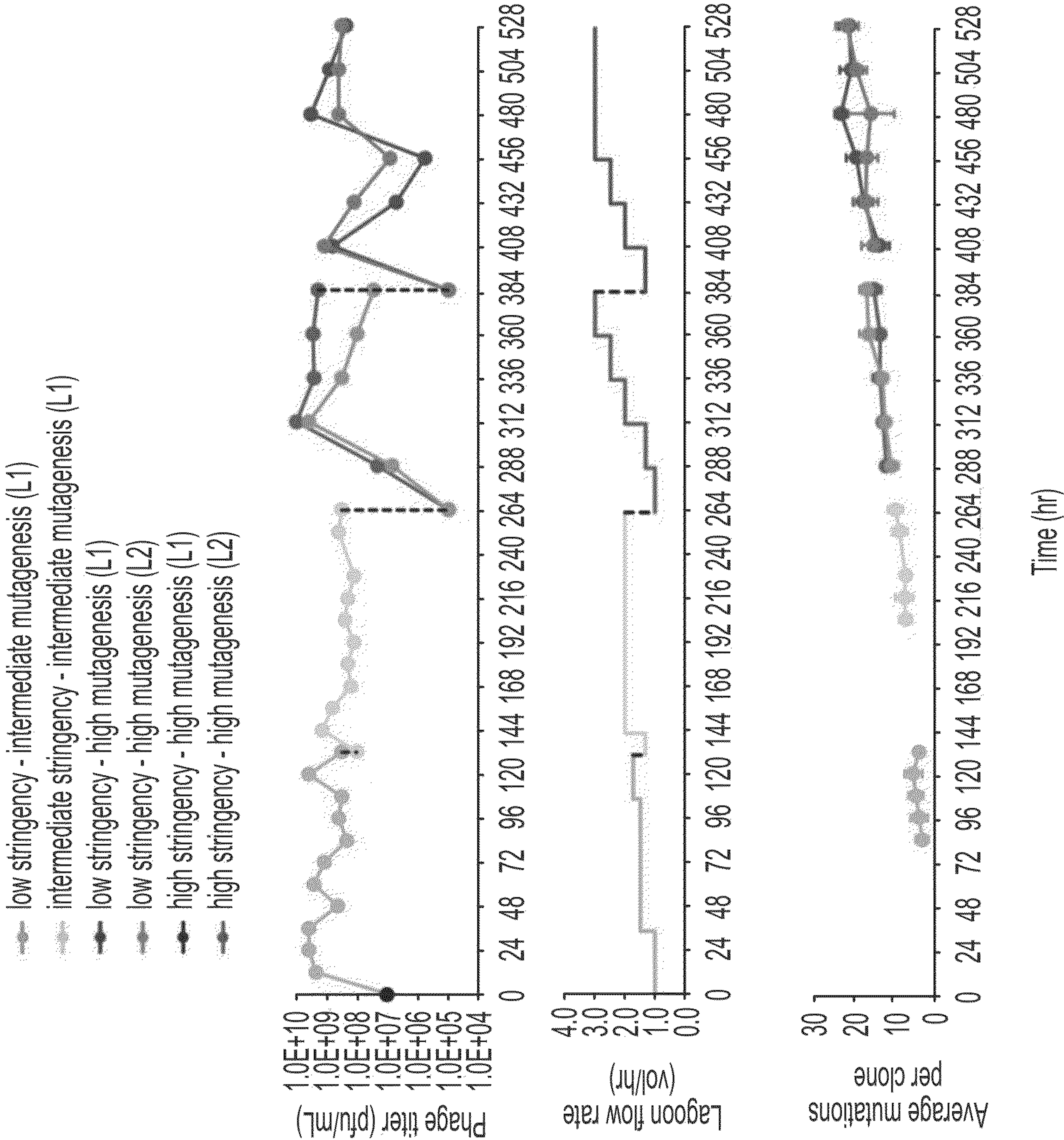


FIG. 8B

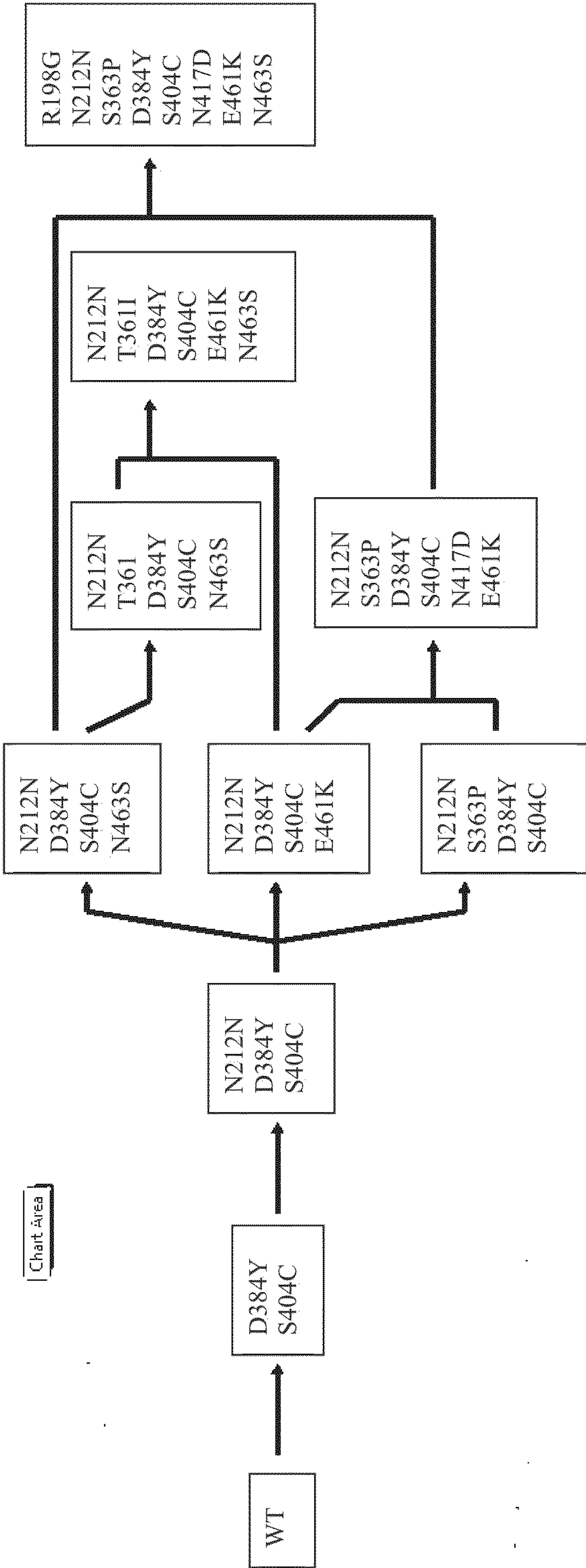


FIG. 9A

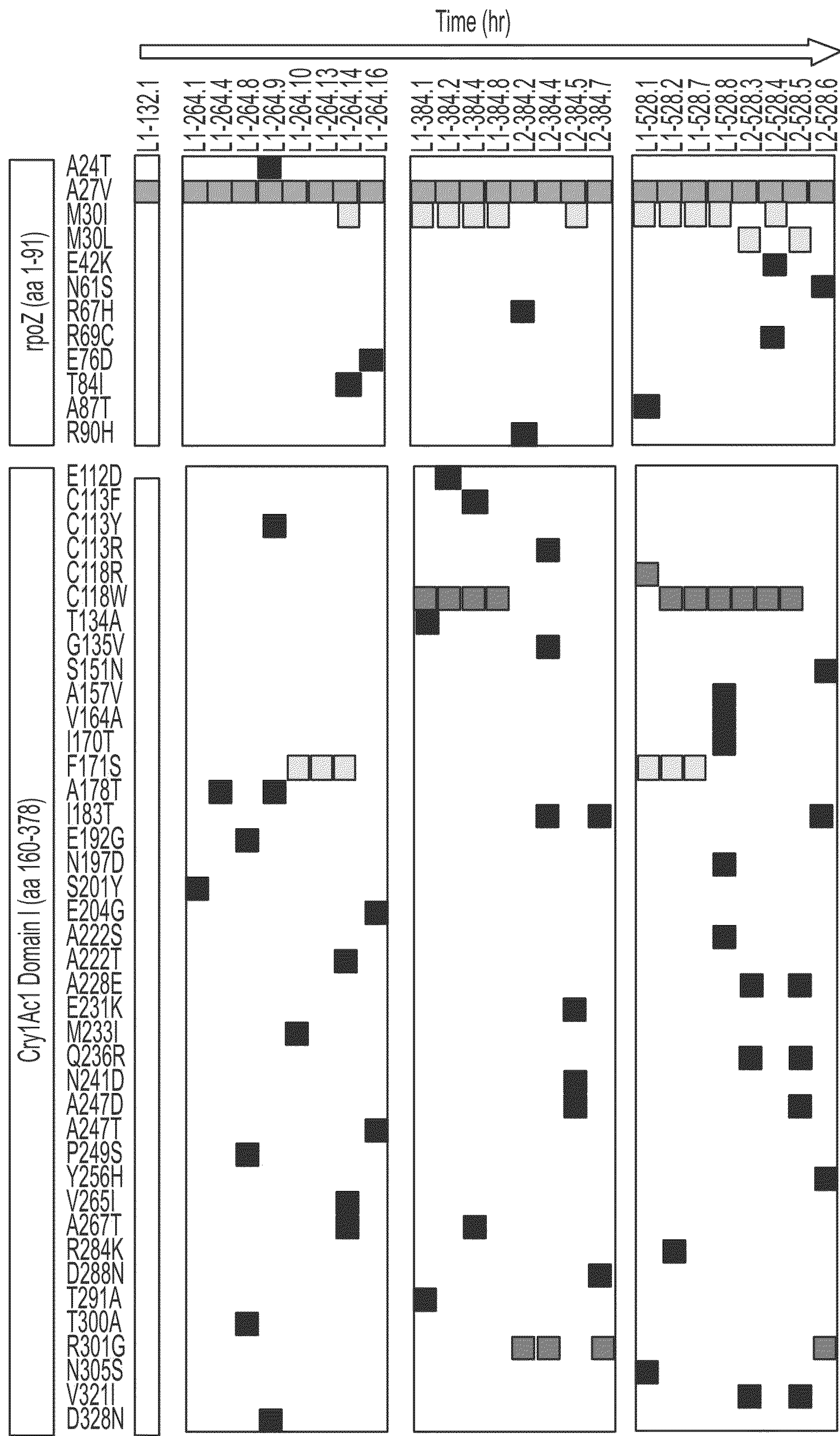


FIG. 9C

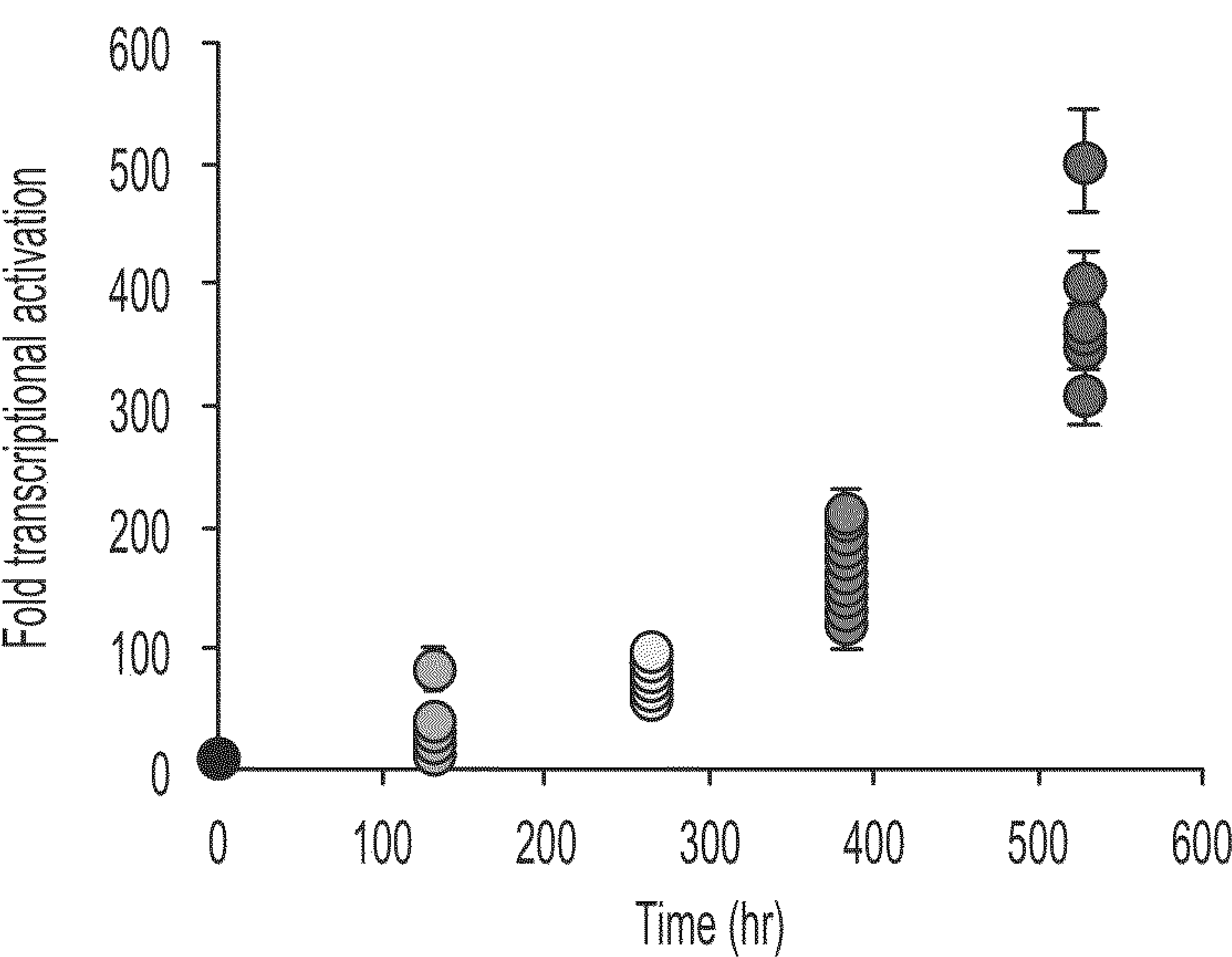
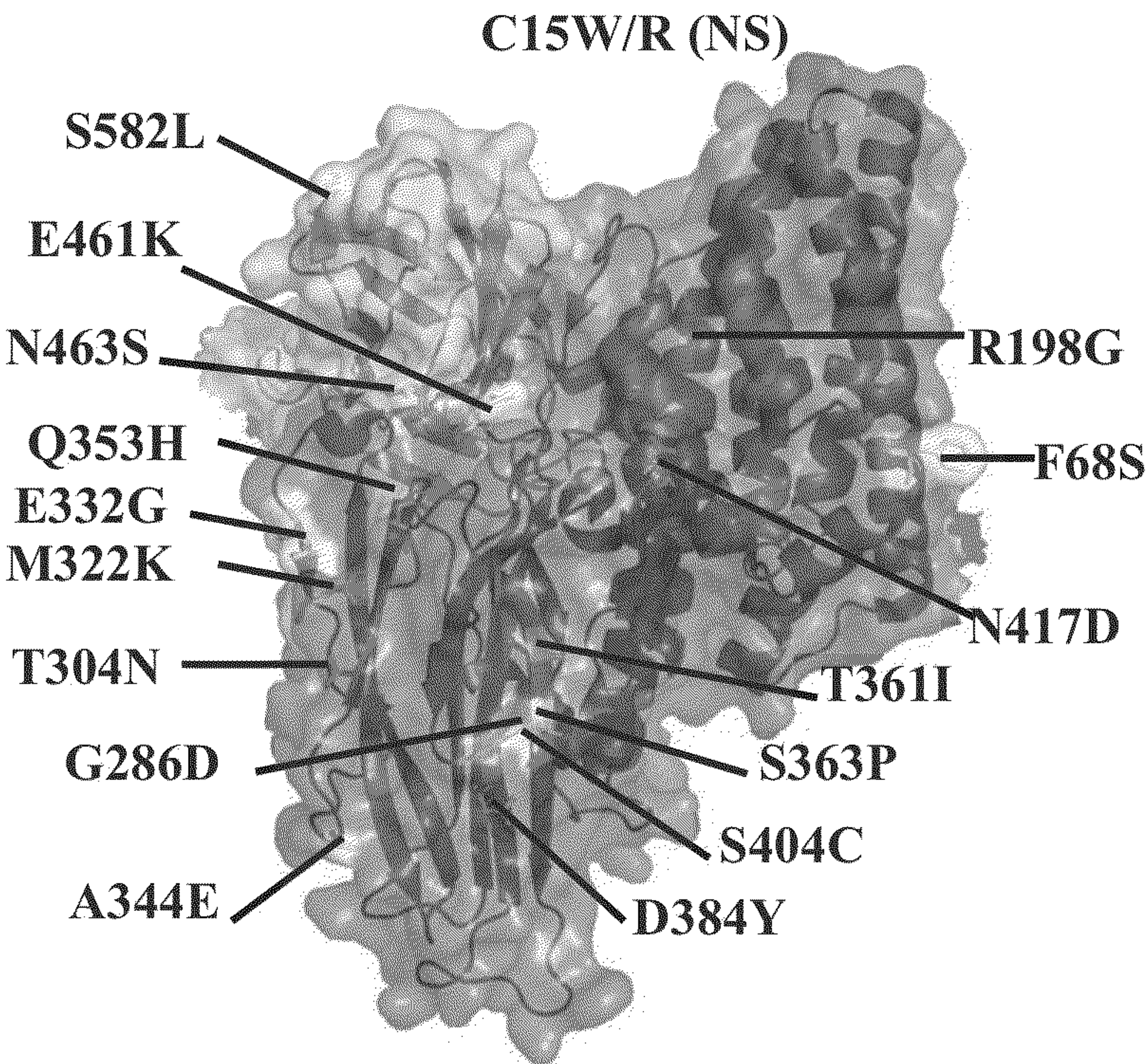


FIG. 10

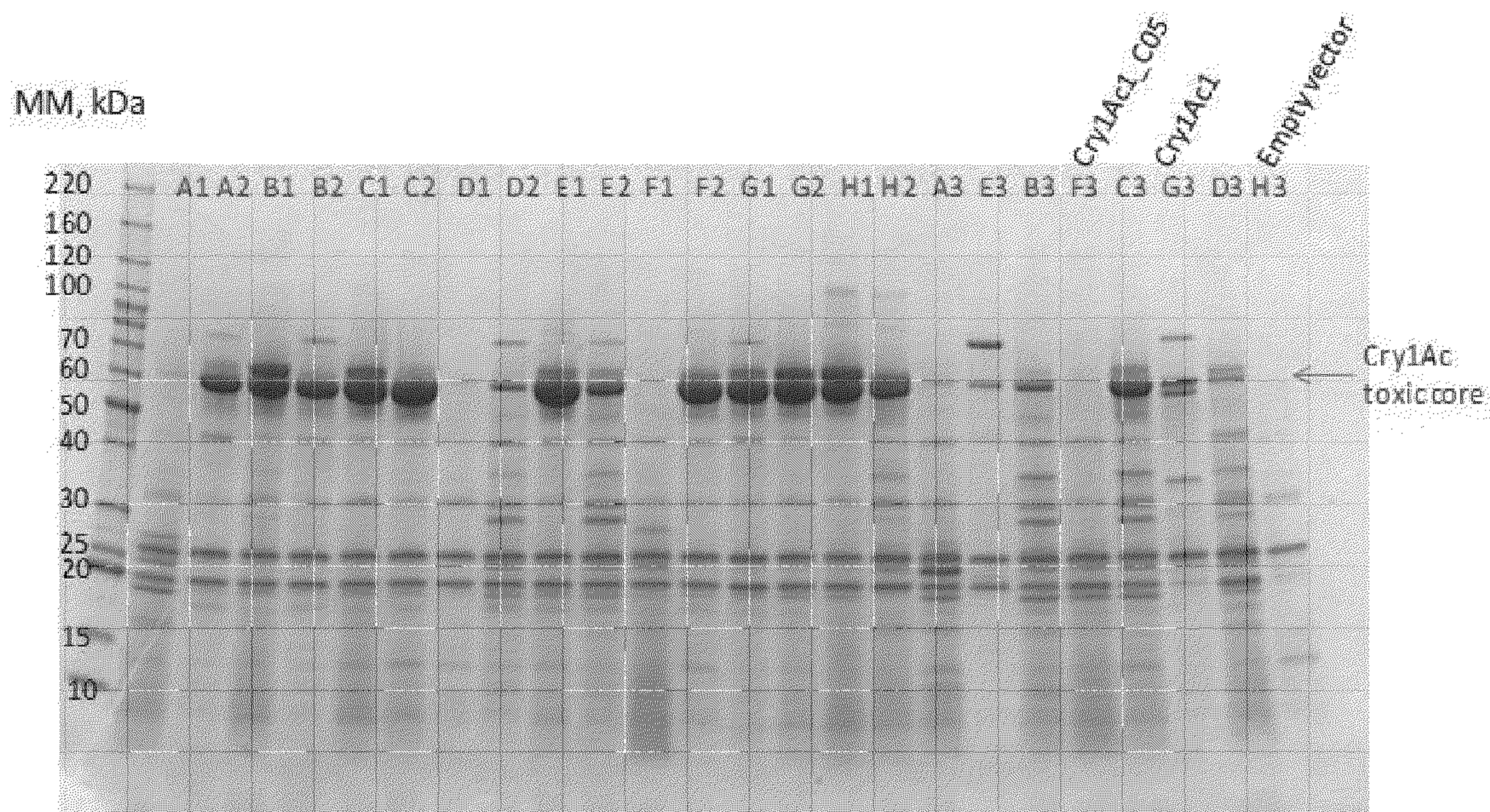
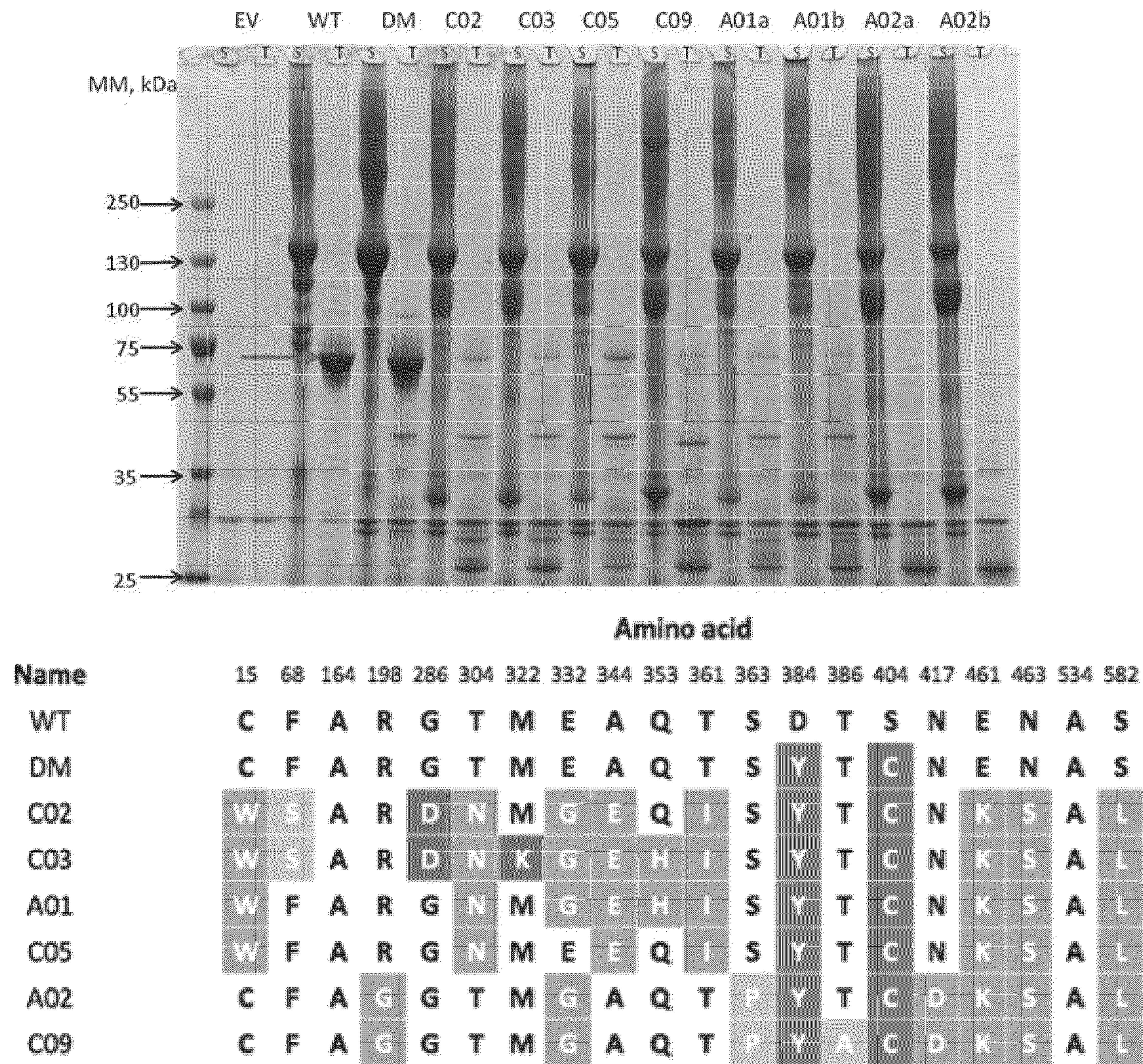


FIG. 11

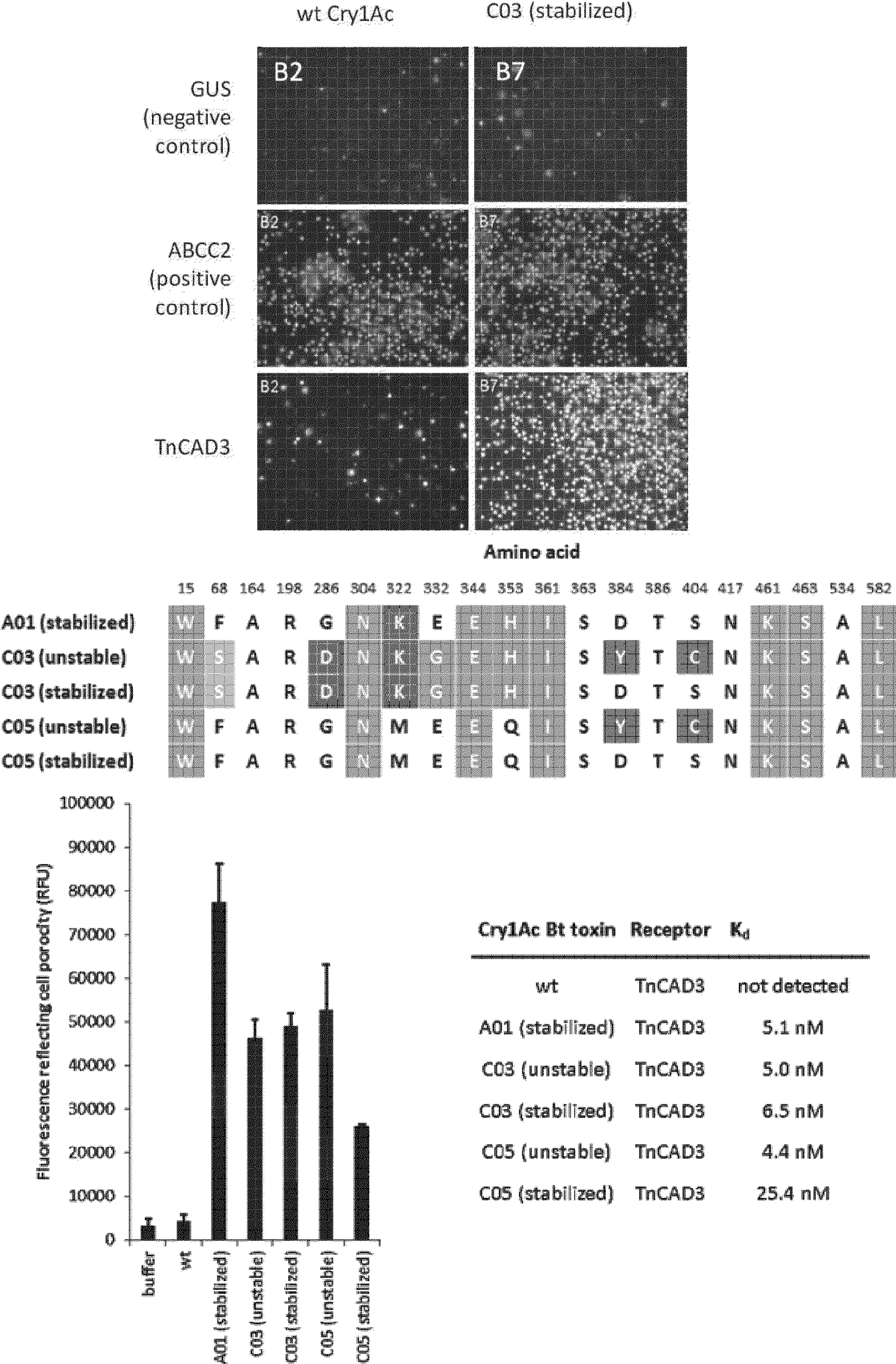


FIG. 12

PACE-evolved variant activity – *T. ni* larva

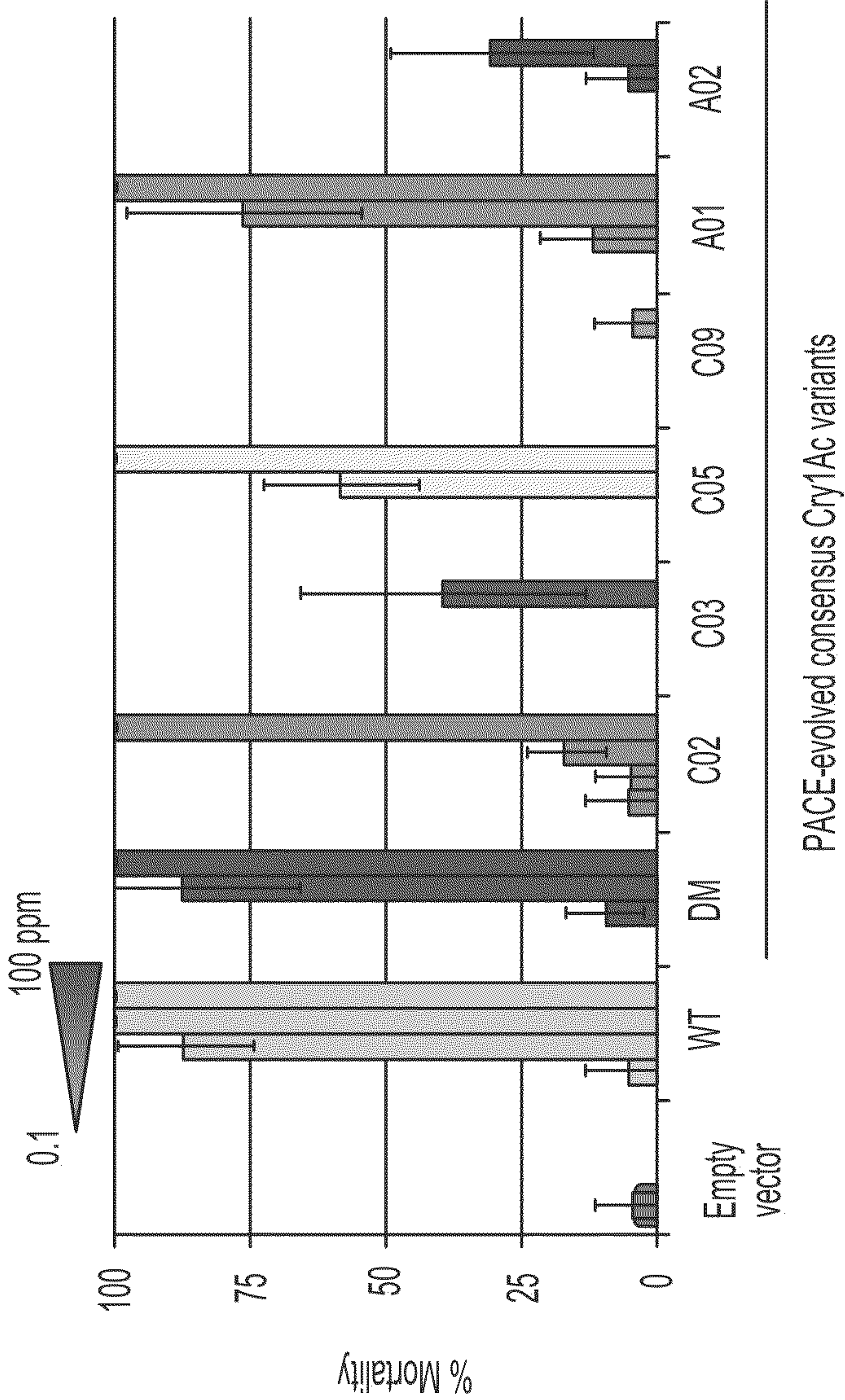


FIG. 13

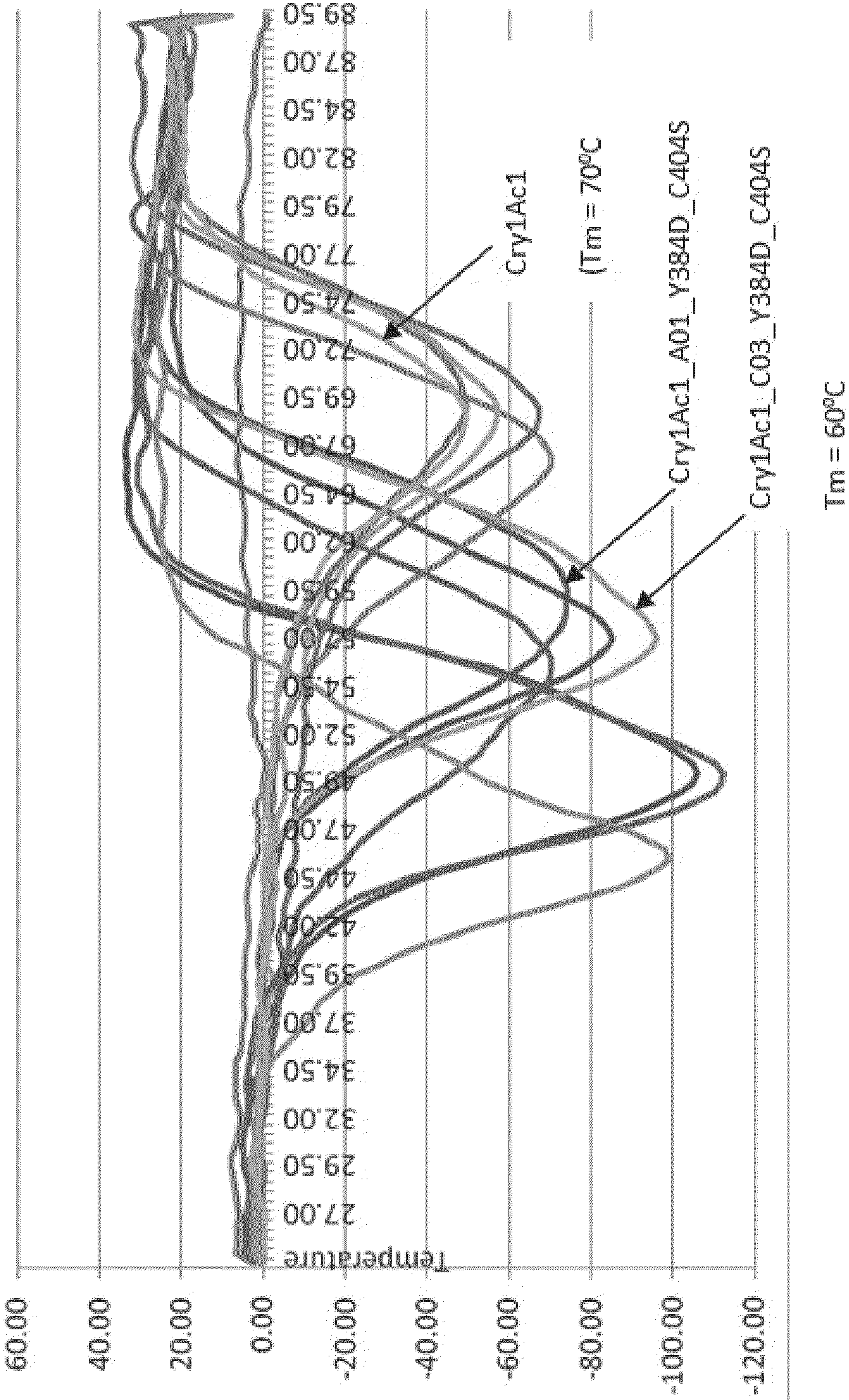


FIG. 14A

PACE-evolved variant activity – affinity

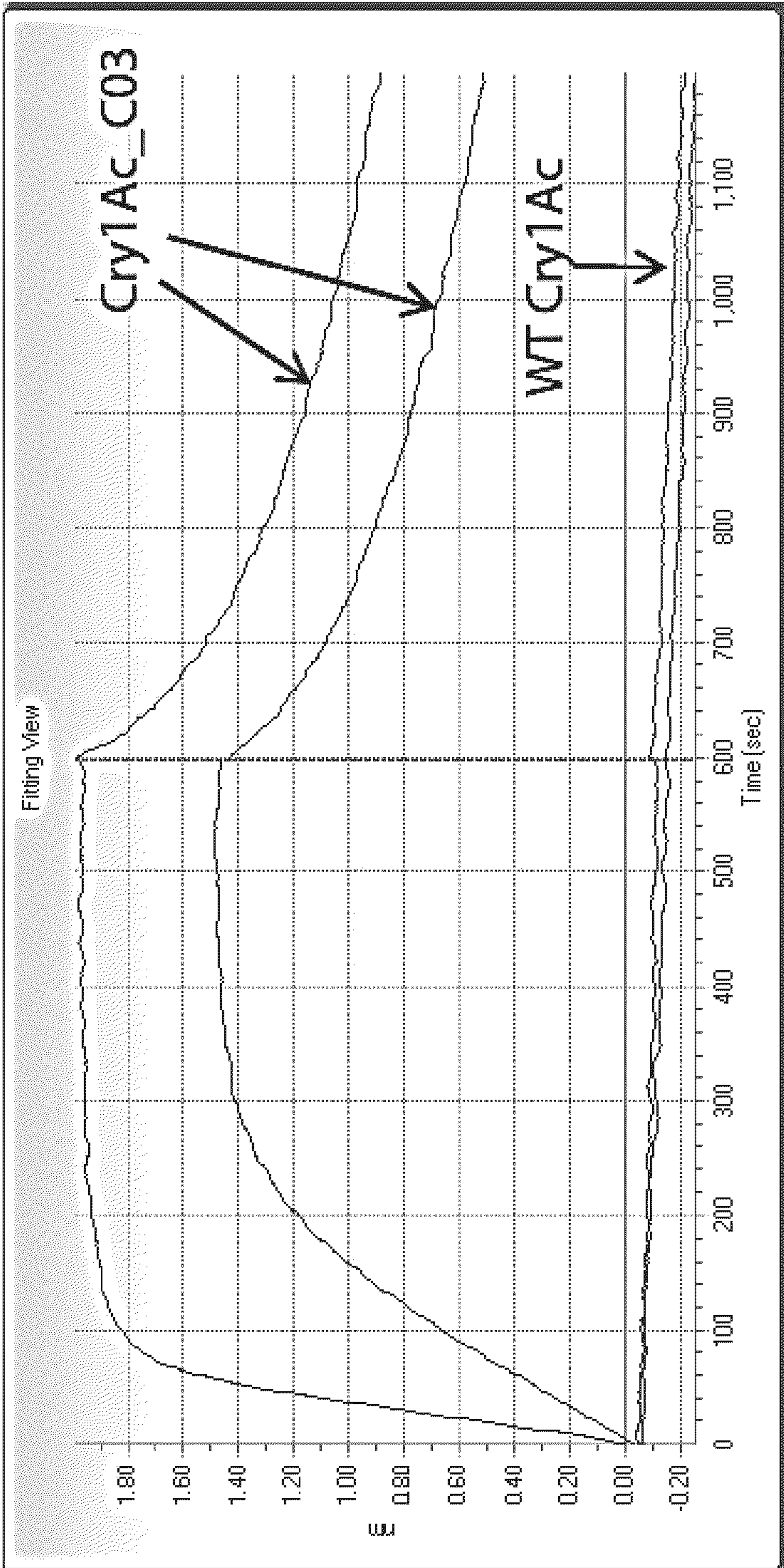


FIG. 14B

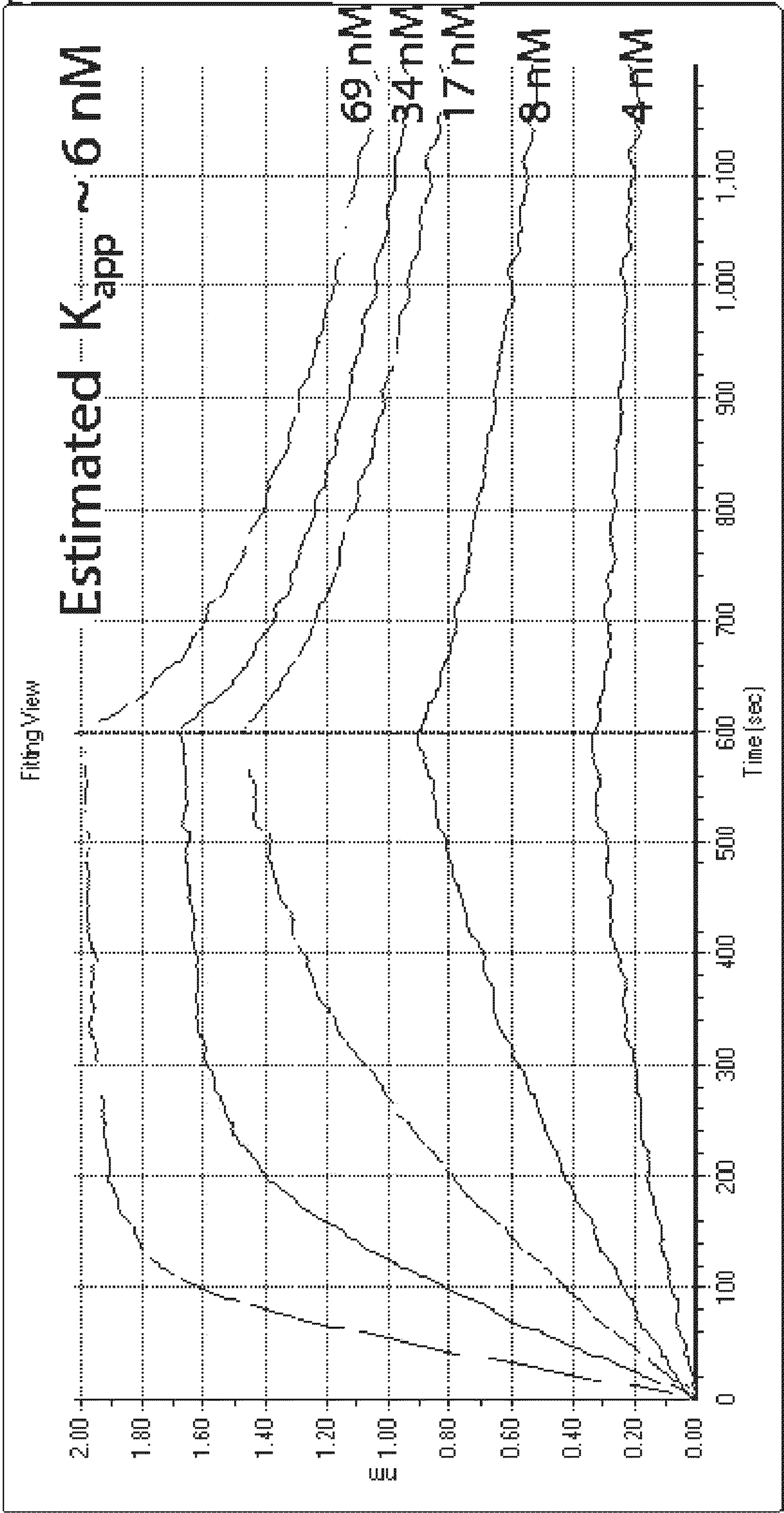


FIG. 14C

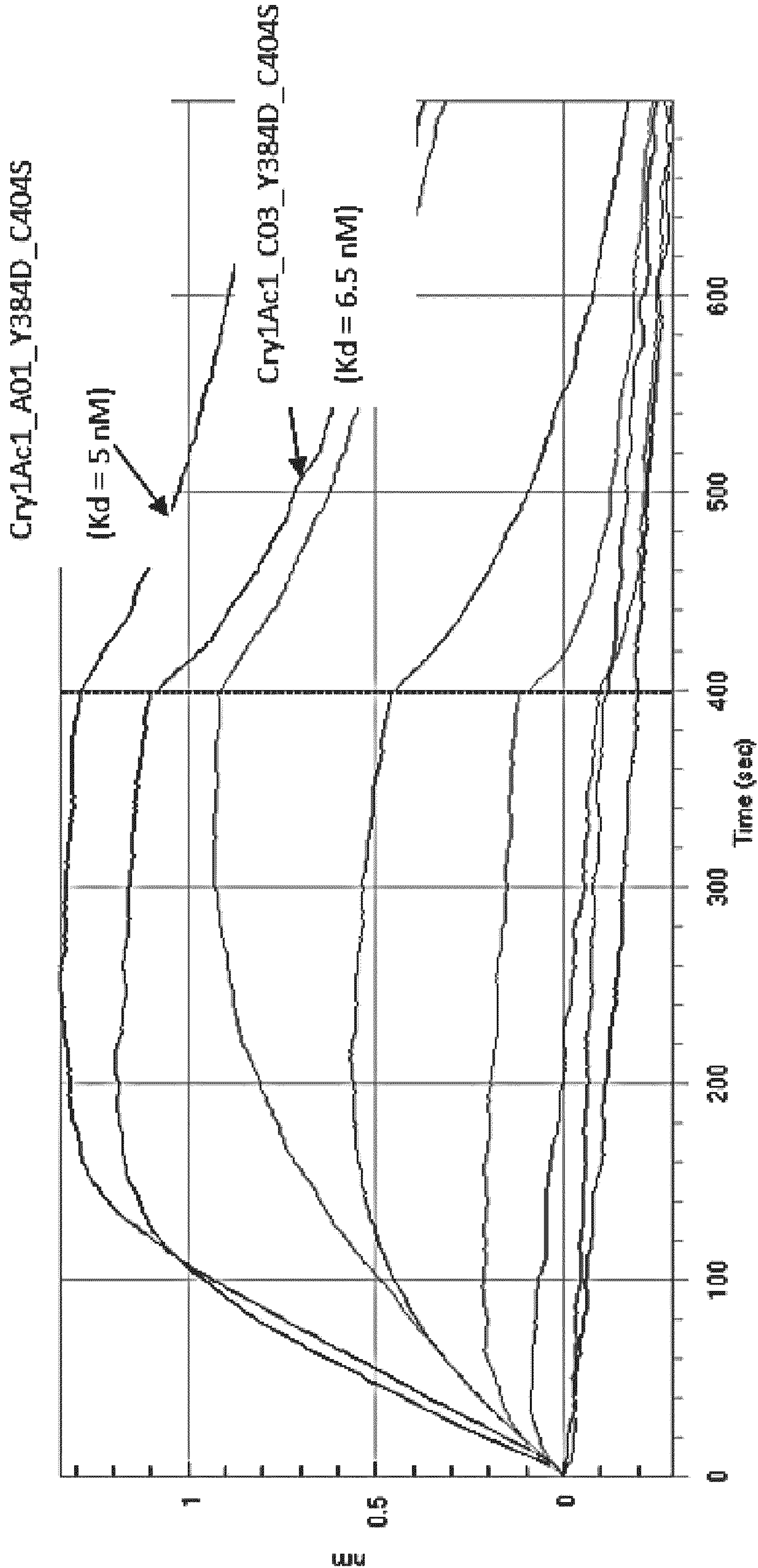


FIG. 15

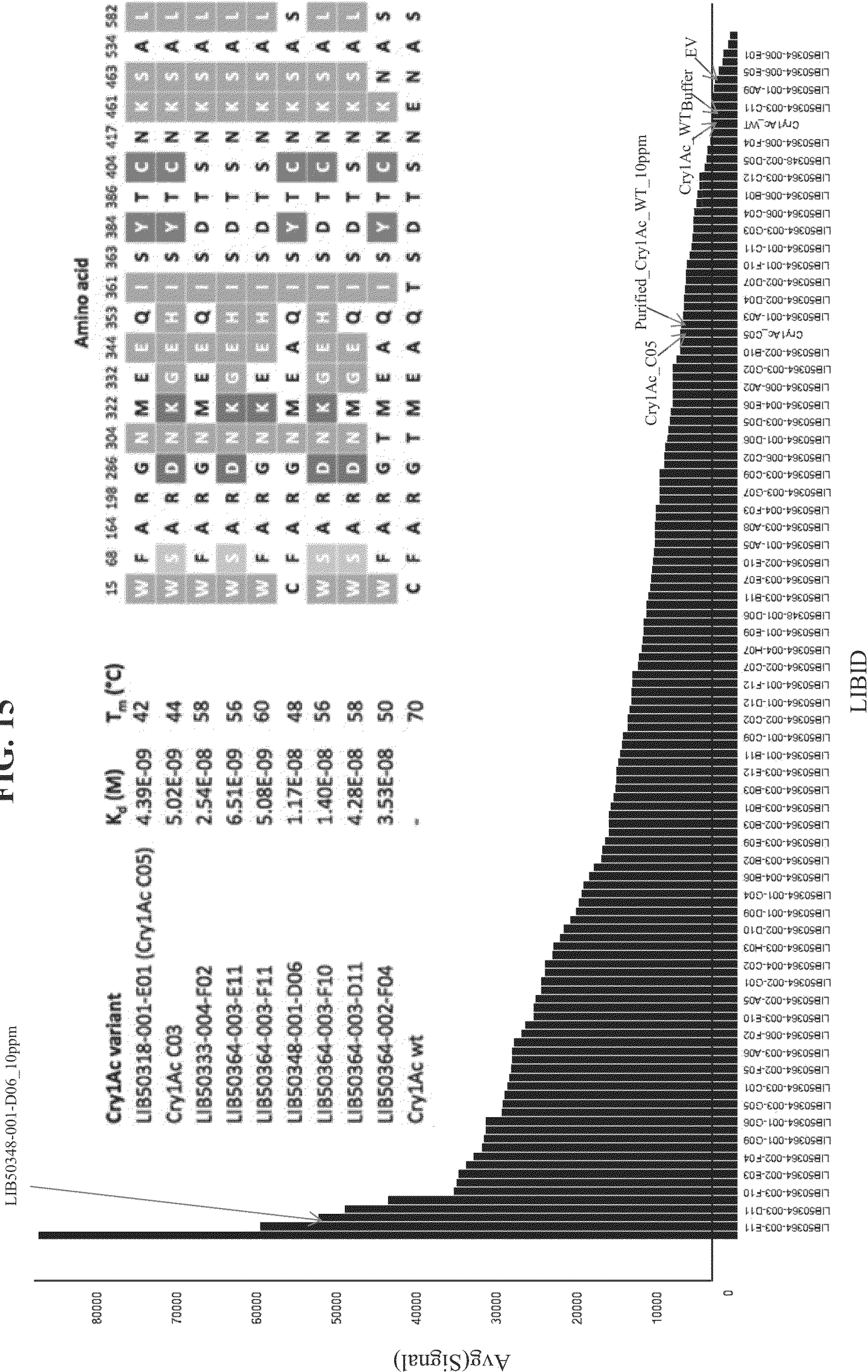
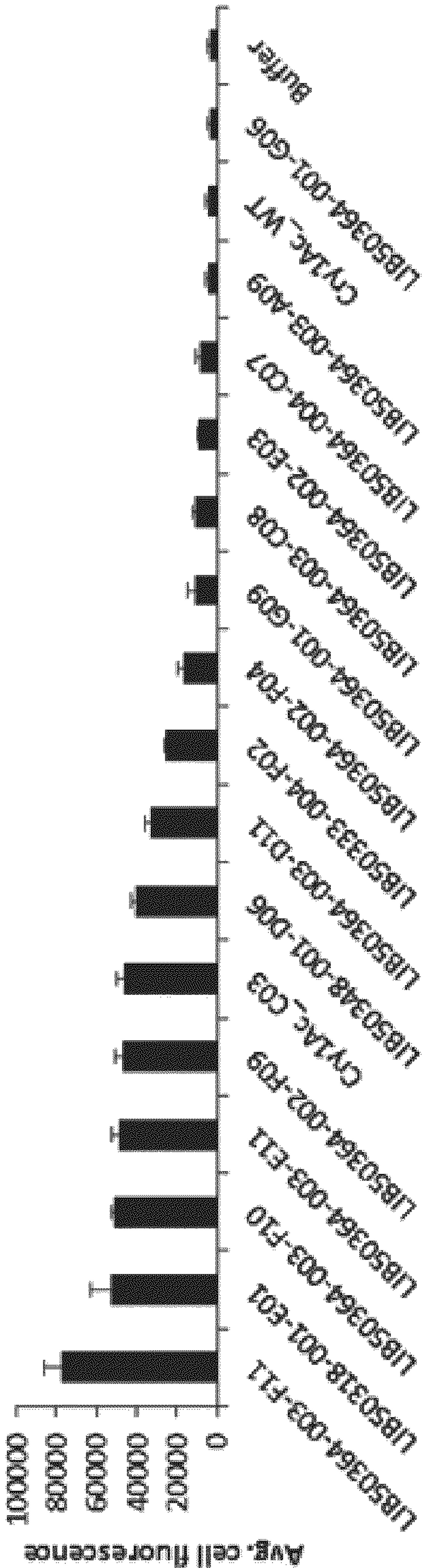


FIG. 16



Target	Cry1Ac variant	K _d (M)	T _m (°C)	Amino acid																							
TBRwt	LIB50318-001-E01 (Cry1Ac C05)	4.39E-09	42	W	F	A	R	G	N	M	E	E	Q	I	S	Y	T	C	N	K	S	A	L	A	S		
TBRwt	Cry1Ac C03	5.02E-09	44	W	S	A	R	D	N	K	G	E	H	I	S	Y	T	C	N	K	S	A	L	A	S		
TBRwt	LIB50333-004-F02	2.54E-08	58	W	F	A	R	G	N	M	E	E	Q	I	S	D	T	S	N	K	S	A	L	A	S		
TBRwt	LIB50364-003-E11	6.51E-09	56	W	S	A	R	D	N	K	G	E	H	I	S	D	T	S	N	K	S	A	L	A	S		
TBRwt	LIB50364-003-F11	5.08E-09	60	W	F	A	R	G	N	K	E	E	H	I	S	D	T	S	N	K	S	A	L	A	S		
TBRwt	LIB50348-001-D06	1.17E-08	48	C	F	A	R	G	N	M	E	A	Q	I	S	Y	T	C	N	K	S	A	L	A	S		
TBRwt	LIB50364-003-F10	1.40E-08	56	W	S	A	R	D	N	K	G	E	H	I	S	D	T	C	N	K	S	A	L	A	S		
TBRwt	LIB50364-003-D11	4.28E-08	58	W	S	A	R	D	N	M	G	E	Q	I	S	D	T	S	N	K	S	A	L	A	S		
TBRwt	LIB50364-002-F04	3.53E-08	50	W	F	A	R	G	T	M	E	A	Q	I	S	Y	T	C	N	K	N	A	S	A	S		
TBRwt	Cry1Ac wt	-	70	C	F	A	R	G	T	M	E	A	Q	T	S	D	T	S	N	E	N	A	S	A	S		

FIG. 17

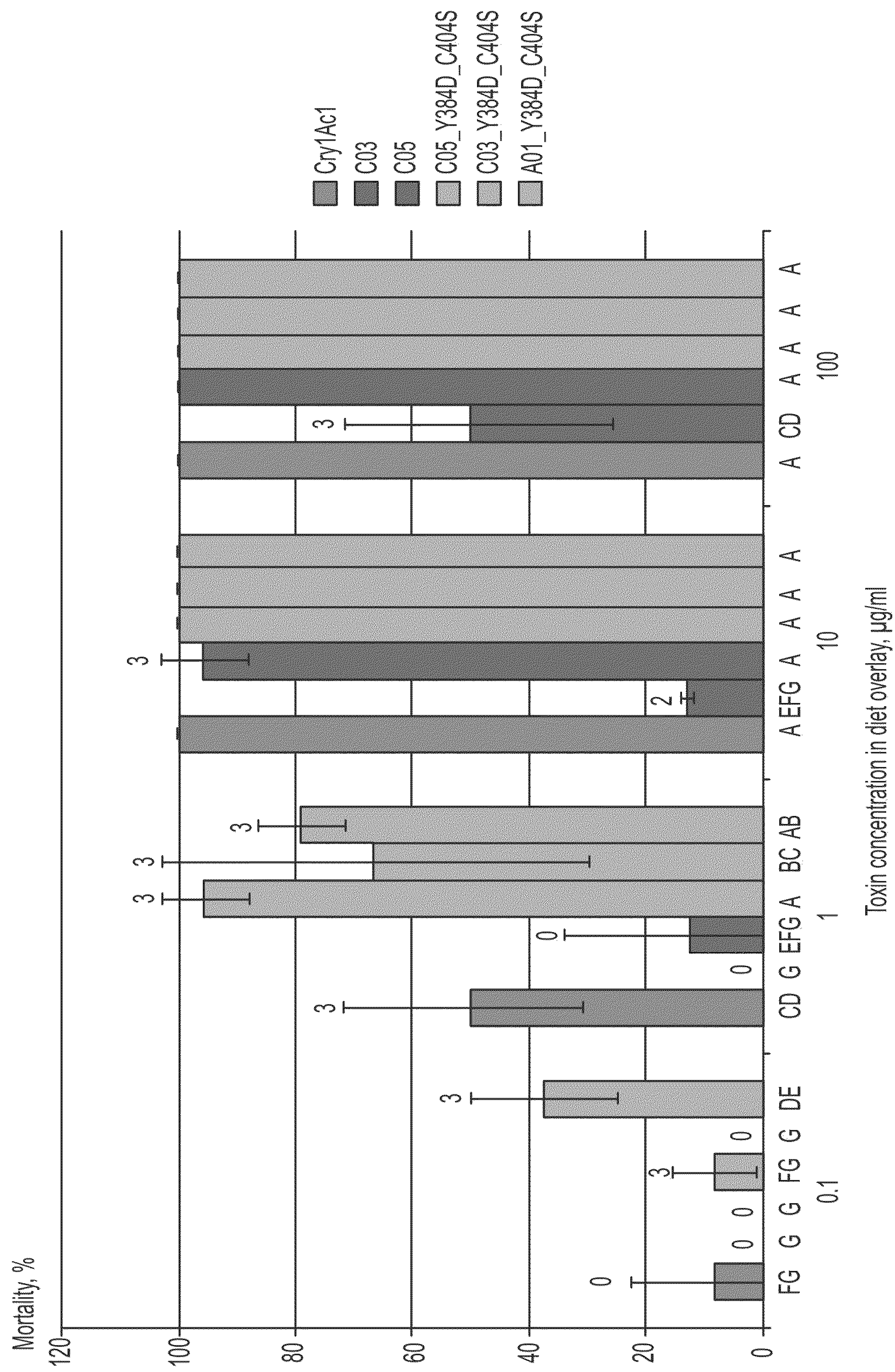


FIG. 18

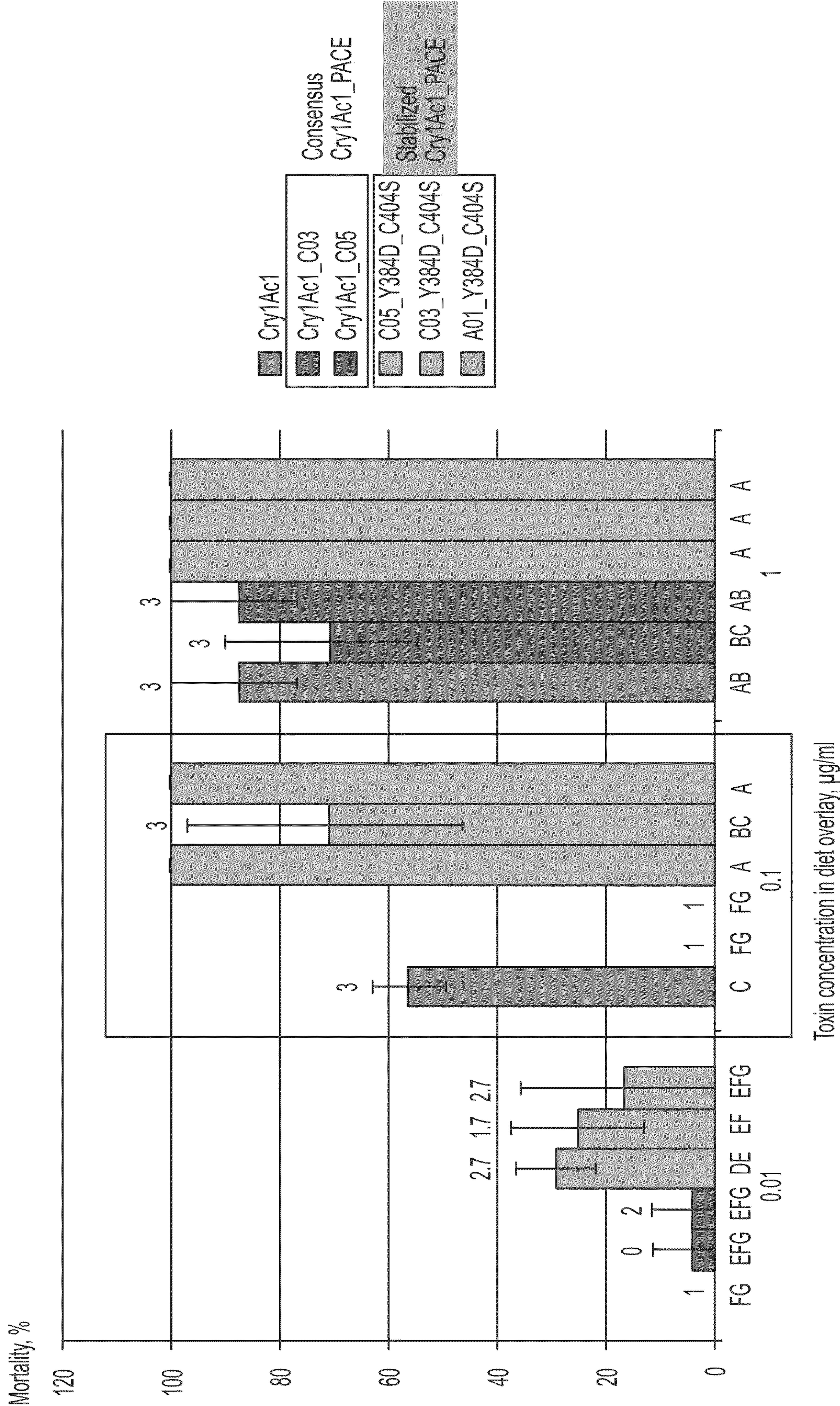


FIG. 19

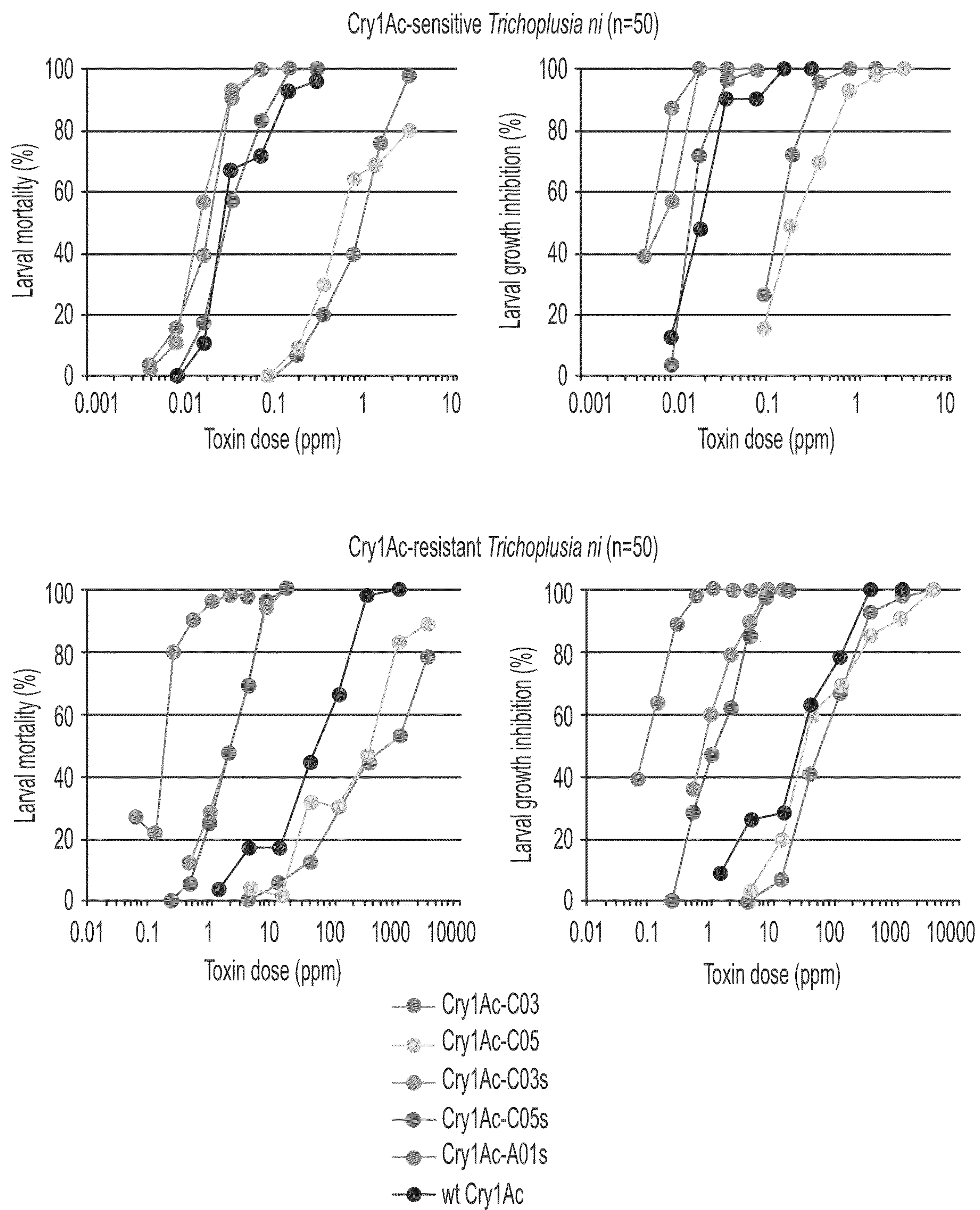


FIG. 20A

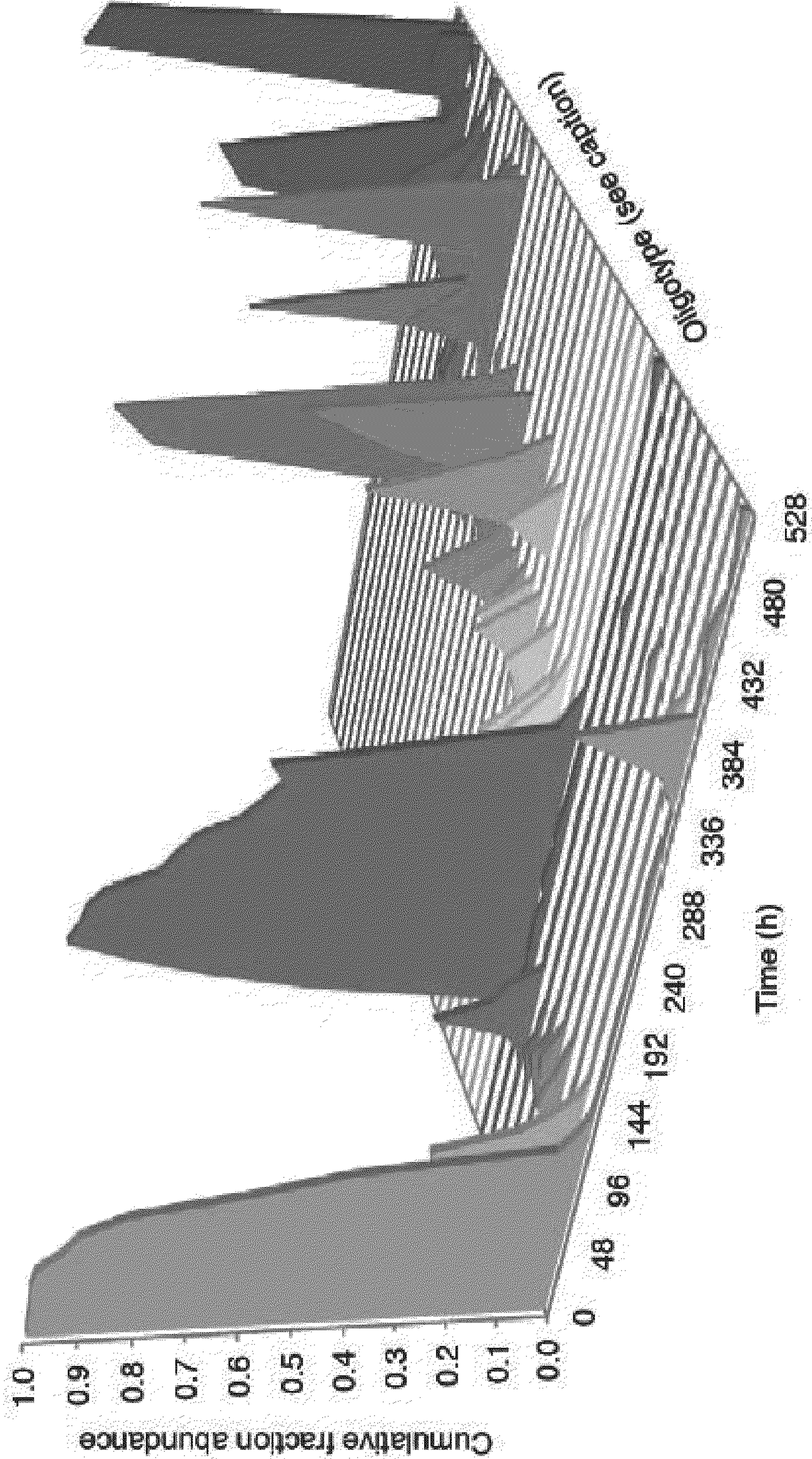


FIG. 20B

Oligotype Number	RpoZ		Cry1Ac																
	-78	-79	15	68	198	286	304	322	344	347	381	383	384	404	417	481	483	515	582
1	A	M	C	F	R	G	T	E	A	Q	T	S	D	S	N	E	N	E	S
2 (8)	V	M	C	F	R	G	T	E	A	Q	T	S	D	S	N	E	N	E	S
3	V	M	C	F	R	G	T	E	A	Q	T	S	D	C	N	E	N	E	S
4 (10)	V	M	C	F	R	G	T	E	A	Q	T	S	Y	S	N	E	N	E	S
5	A	M	C	F	R	G	T	E	A	Q	T	S	Y	C	N	E	N	E	S
6 (9)	V	M	C	F	R	G	T	E	A	Q	T	S	Y	C	N	E	N	E	S
7	A	M	C	F	R	G	T	E	A	Q	T	S	Y	S	N	E	N	E	S
11	V	I	C	F	R	G	T	E	A	Q	T	S	Y	C	N	E	N	E	S
12	V	M	C	F	R	G	T	E	A	Q	T	P	Y	C	N	E	N	E	S
13	V	M	C	F	R	G	T	E	A	Q	I	S	Y	C	N	E	N	E	S
14	V	M	C	F	R	G	T	E	A	Q	T	S	Y	C	N	K	N	E	S
15	V	M	C	S	R	G	T	E	A	Q	T	S	Y	C	N	E	N	E	S
16	V	M	C	F	R	G	T	E	A	Q	T	P	Y	C	D	K	N	E	S
17	V	I	C	F	R	G	T	E	A	Q	T	S	Y	C	N	K	N	E	S
18	V	I	C	F	R	G	T	E	A	Q	T	P	Y	C	D	K	N	E	S
19	V	I	W	F	R	G	T	E	A	Q	I	S	Y	C	N	E	S	E	S
20	V	I	W	F	R	G	T	E	A	Q	I	S	Y	C	N	K	S	E	S
21	V	I	W	F	R	G	N	E	A	Q	I	S	Y	C	N	K	S	E	S
22	V	I	W	F	R	G	N	E	E	Q	I	S	Y	C	N	K	S	E	S
23	V	I	W	F	R	G	N	E	E	Q	I	S	Y	C	N	K	S	E	L
24	V	I	W	F	R	G	T	E	E	Q	I	S	Y	C	N	K	S	E	L
25	V	I	C	F	R	G	N	E	E	Q	I	S	Y	C	N	K	S	E	L
26	V	I	W	F	R	G	N	E	A	Q	I	S	Y	C	N	K	S	E	L
27 (32)	V	I	W	F	R	G	N	E	E	R	I	S	Y	C	N	K	S	E	L
28	V	M	C	F	G	G	T	E	A	Q	T	P	Y	C	D	K	S	E	S
29	V	M	C	F	G	G	T	G	A	Q	T	P	Y	C	D	K	S	E	S
30 (33)	V	I	W	F	R	G	N	G	E	Q	I	S	Y	C	N	K	S	E	L
31 (34)	V	I	W	F	R	G	N	E	E	R	I	S	Y	C	N	K	S	K	L
35 (36)	V	I	W	S	R	D	N	G	E	Q	I	S	Y	C	N	K	S	E	L
37	V	I	W	S	R	G	N	G	E	Q	I	S	Y	C	N	K	S	E	L

FIG. 20C

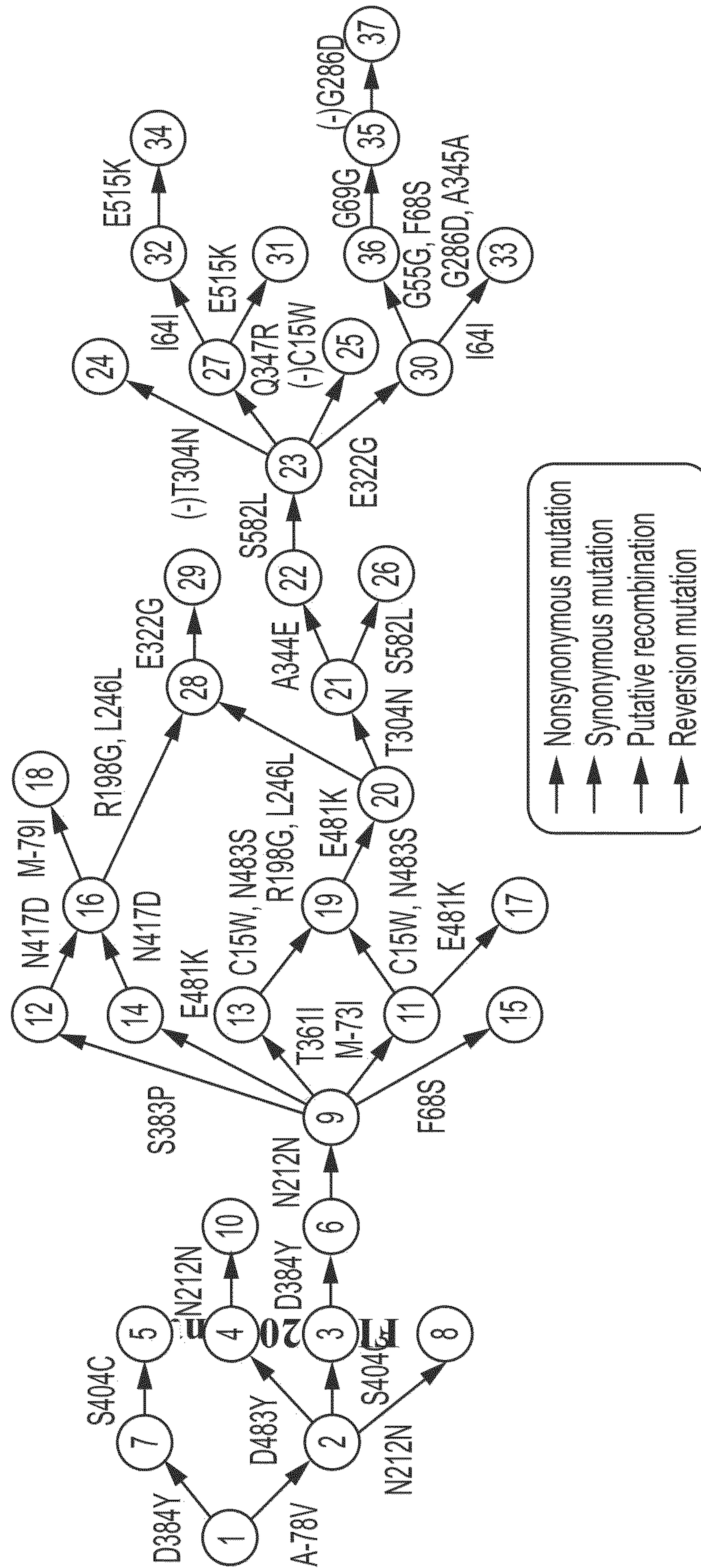


FIG. 21A

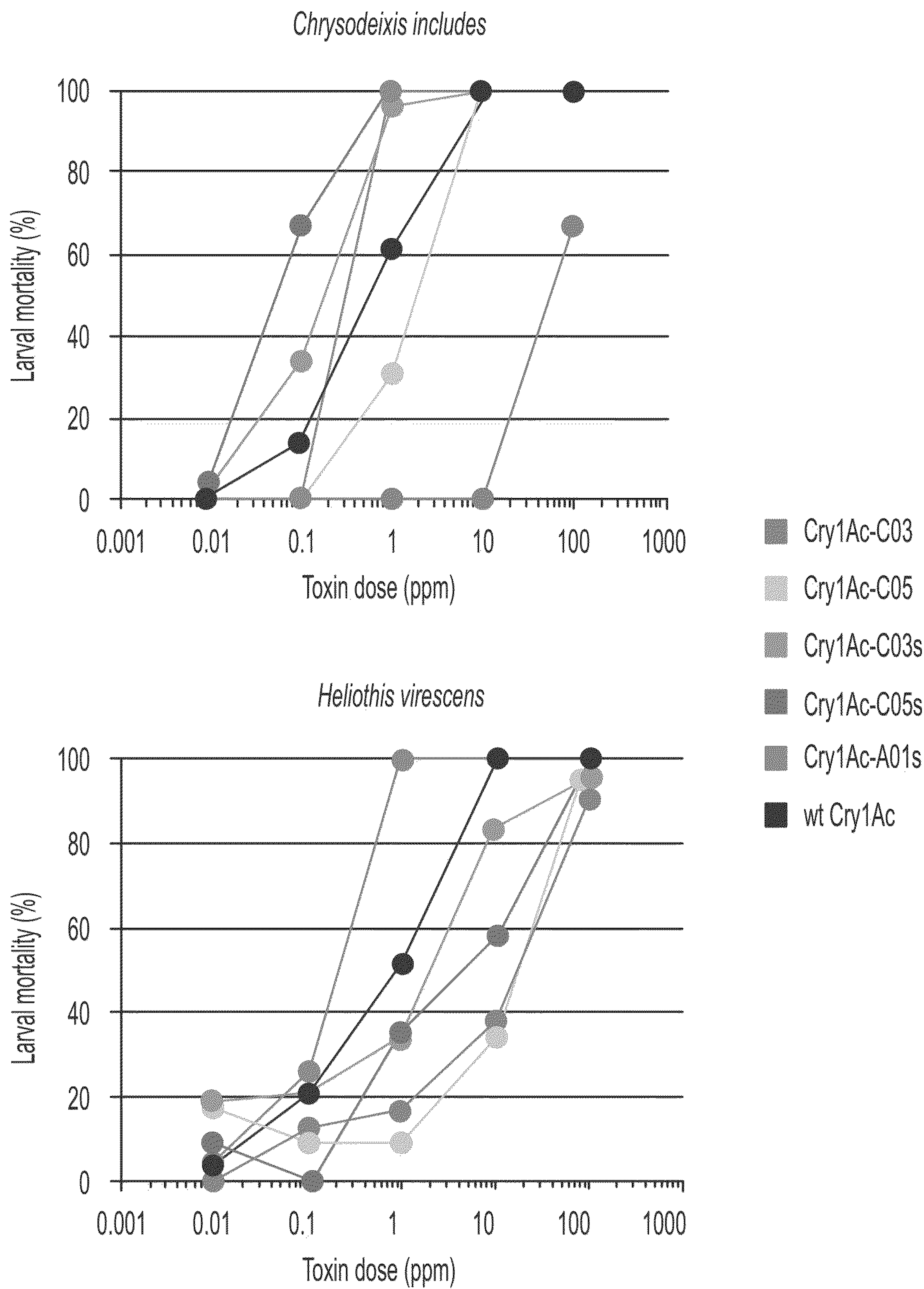


FIG. 21B

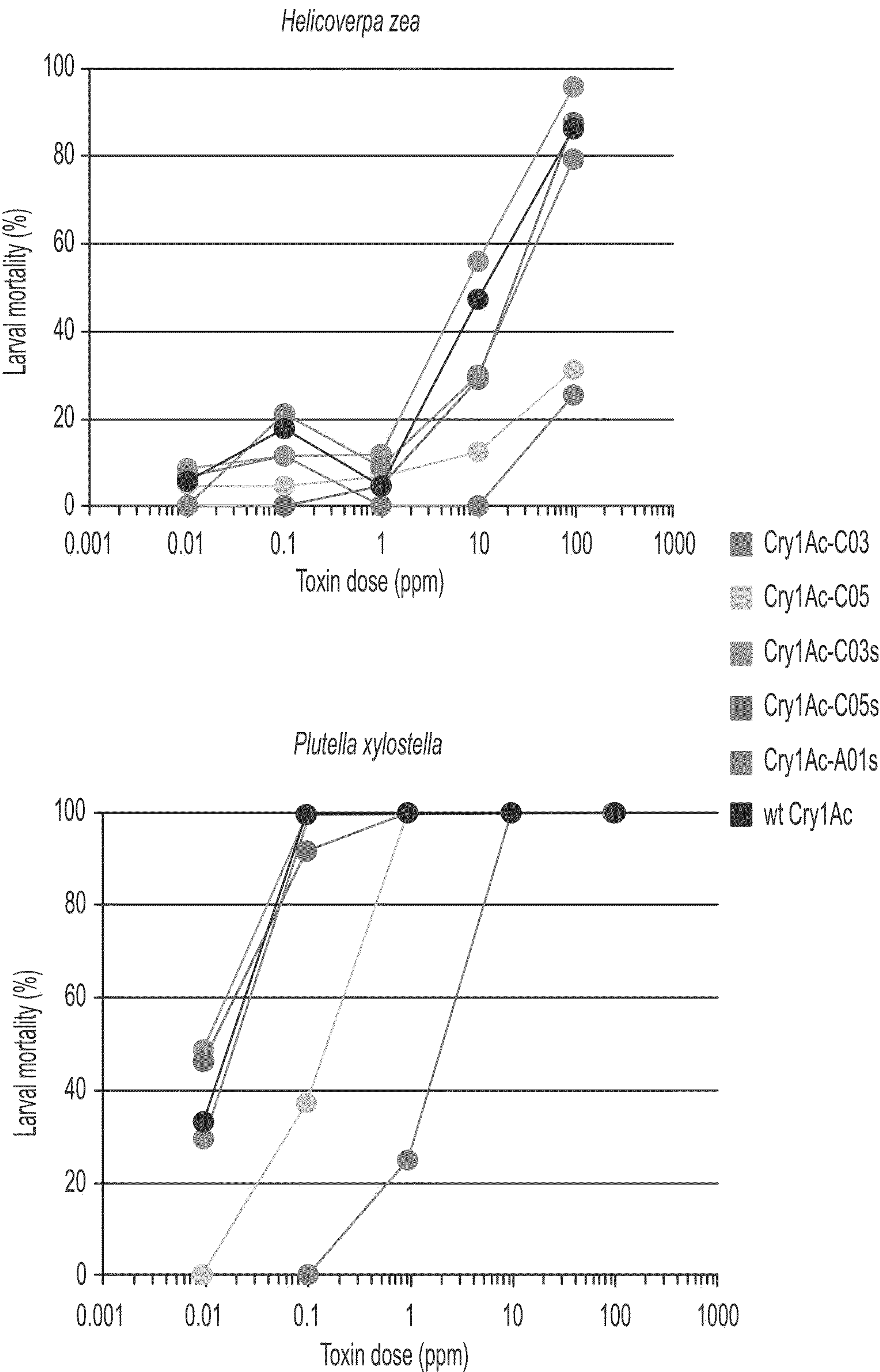


FIG. 21C

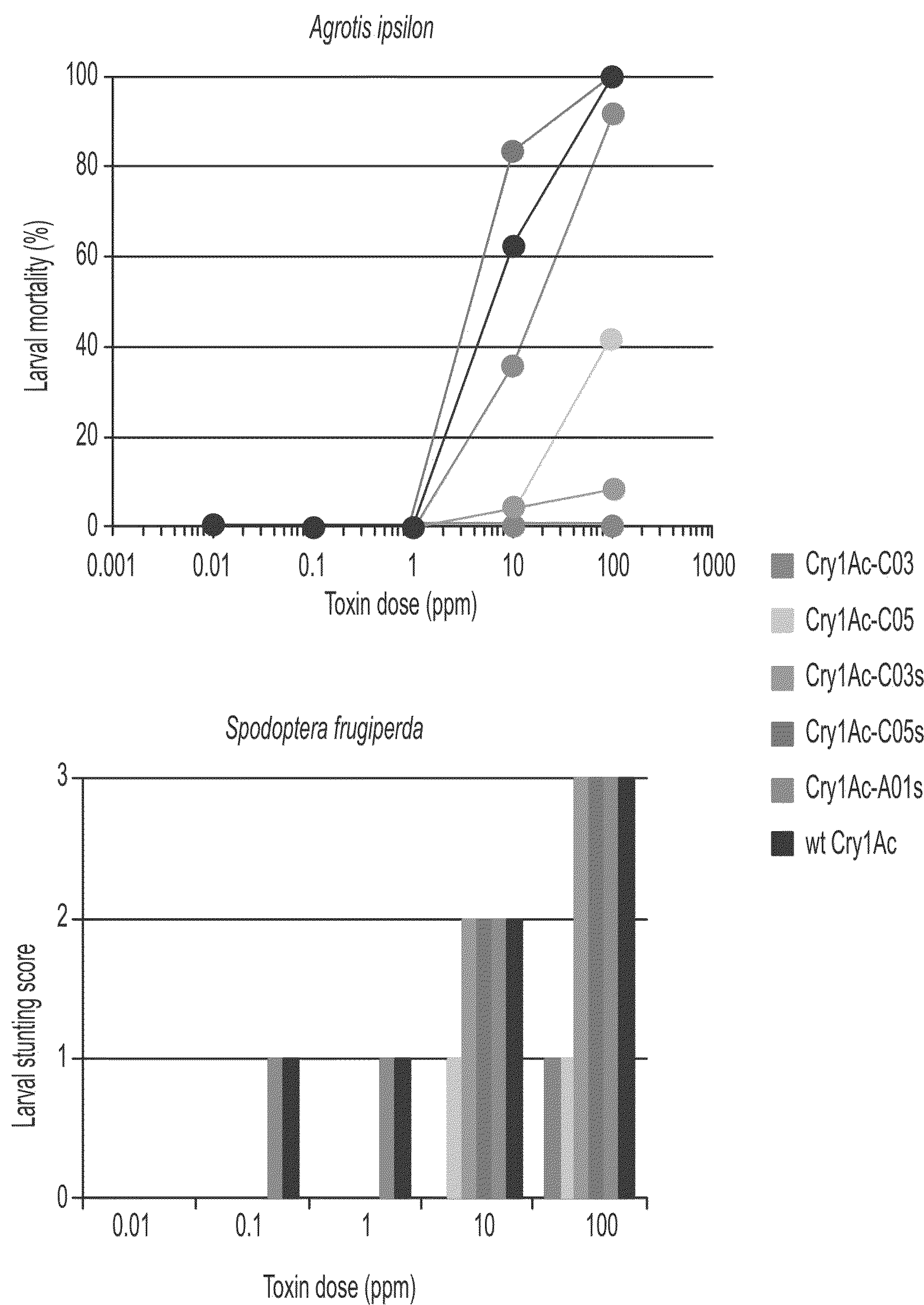


FIG. 21D

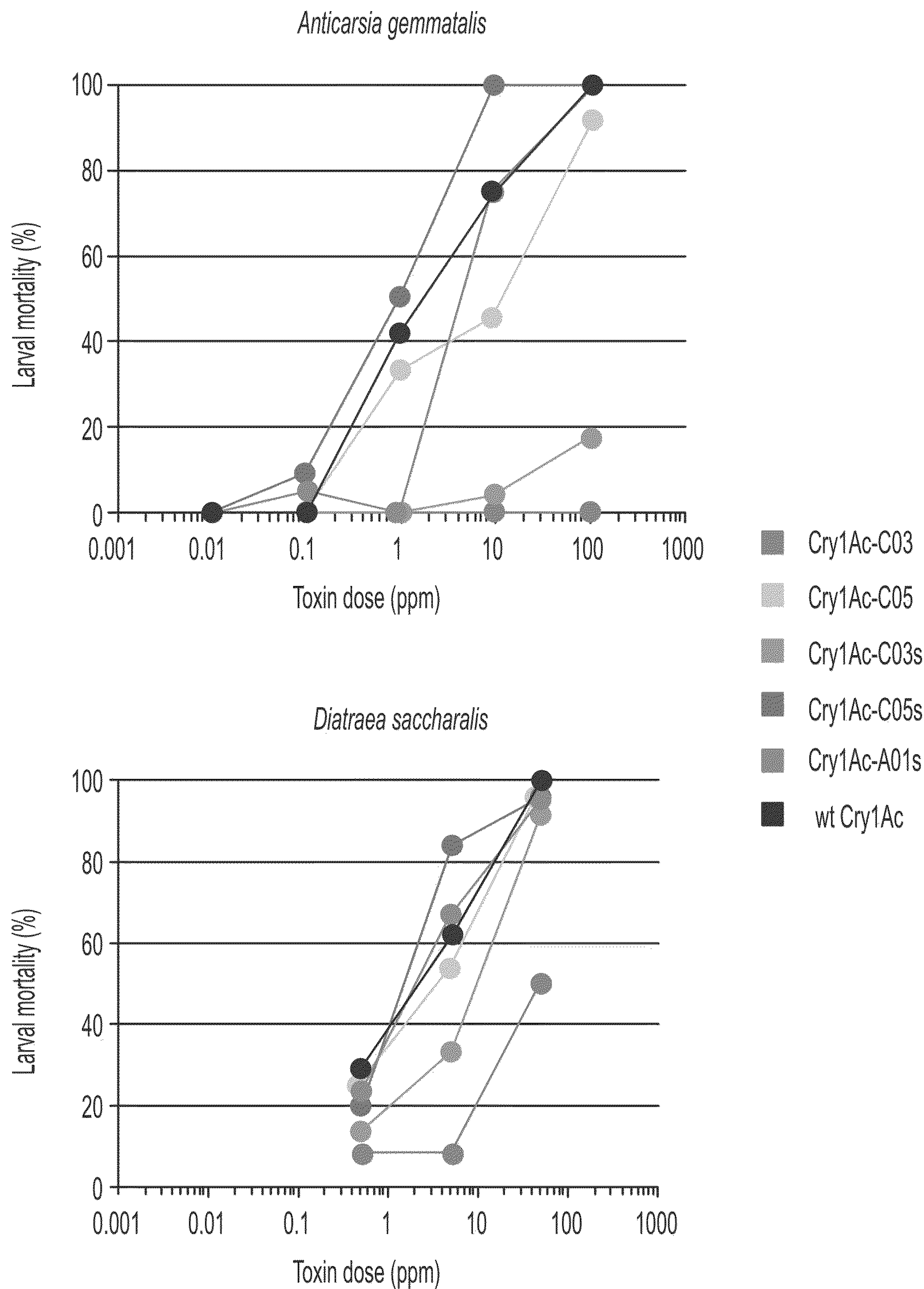
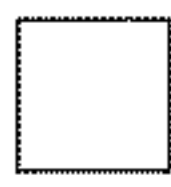
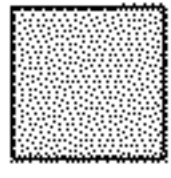
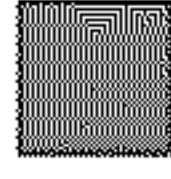


FIG. 22

	<i>T. ni</i>	<i>C. includens</i>	<i>H. virescens</i>	<i>H. zea</i>	<i>P. xylostella</i>	<i>A. ipsilon</i>	<i>S. frugiperda</i>	<i>L. decemlineata</i>	<i>D. virgifera</i>
<i>T. ni</i>	-	78.6 (1362)	57.9 (1004)	57.3 (993)	53.1 (920)	51.8 (897)	51.2 (888)	25.6 (443)	26.1 (453)
<i>C. includens</i>	76.8 (1362)	-	55.7 (988)	54 (958)	51.8 (918)	49.9 (884)	49.8 (883)	24.6 (437)	25.5 (452)
<i>H. virescens</i>	58 (1004)	57 (988)	-	84.5 (1464)	55.4 (959)	58.9 (1021)	57.3 (992)	26 (451)	25.7 (445)
<i>H. zea</i>	57.4 (993)	55.4 (958)	84.6 (1464)	-	54.6 (945)	58.7 (1016)	57.3 (992)	26.3 (455)	25.4 (439)
<i>P. xylostella</i>	53.6 (920)	53.5 (918)	55.9 (959)	55 (945)	-	49.4 (848)	50.5 (867)	24.6 (422)	25.3 (435)
<i>A. ipsilon</i>	51 (897)	50.2 (884)	58 (1021)	57.7 (1016)	48.2 (848)	-	53.1 (935)	24 (422)	25 (440)
<i>S. frugiperda</i>	51.2 (888)	50.9 (883)	57.2 (992)	57.2 (992)	50 (867)	53.9 (935)	-	25.7 (445)	25.1 (436)
<i>L. decemlineata</i>	26.3 (443)	25.9 (437)	26.7 (451)	27 (455)	25 (422)	25 (422)	26.4 (445)	-	39.6 (668)
<i>D. virgifera</i>	26.8 (453)	26.8 (452)	26.4 (445)	26 (439)	25.8 (435)	26.1 (440)	25.8 (436)	39.6 (668)	-

	<i>T. ni</i>	<i>C. includens</i>	<i>H. virescens</i>	<i>H. zea</i>	<i>P. xylostella</i>	<i>A. ipsilon</i>	<i>S. frugiperda</i>	<i>L. decemlineata</i>	<i>D. virgifera</i>
<i>T. ni</i>	-	76.9 (170)	55.2 (122)	54.3 (120)	52 (115)	47.5 (105)	47.1 (104)	24 (53)	22.2 (49)
<i>C. includens</i>	75.2 (170)	-	51.3 (116)	51.3 (116)	47.8 (108)	42.5 (96)	42.5 (96)	22.6 (51)	22.6 (51)
<i>H. virescens</i>	55 (122)	52.3 (116)	-	81.5 (181)	50 (111)	49.5 (110)	47.7 (106)	23.4 (52)	19.8 (44)
<i>H. zea</i>	53.8 (120)	52 (116)	81.2 (181)	-	49.3 (110)	50.2 (112)	47.5 (106)	24.2 (54)	19.3 (43)
<i>P. xylostella</i>	52 (115)	48.9 (108)	50.2 (111)	49.8 (110)	-	43.9 (97)	48 (106)	22.2 (49)	19 (42)
<i>A. ipsilon</i>	47.3 (105)	43.2 (96)	49.5 (110)	50.5 (112)	43.7 (97)	-	42.8 (95)	18.5 (41)	18.9 (42)
<i>S. frugiperda</i>	46.8 (104)	43.2 (96)	47.7 (106)	47.7 (106)	47.7 (106)	42.8 (95)	-	24.8 (55)	23.4 (52)
<i>L. decemlineata</i>	22.3 (53)	21.4 (51)	21.8 (52)	22.7 (54)	20.6 (49)	17.2 (41)	23.1 (55)	-	38.2 (91)
<i>D. virgifera</i>	20.2 (49)	21 (51)	18.1 (44)	17.7 (43)	17.3 (42)	17.3 (42)	21.4 (52)	37.4 (91)	-

 < 40%  < 70%  > 70%

EVOLUTION OF BT TOXINS

RELATED APPLICATIONS

[0001] This application is a divisional of and claims priority under 35 U.S.C. § 120 to U.S. Pat. Application, U.S.S.N. 15/217,839, filed Jul. 22, 2016, which claims priority to U.S. Provisional Applications, U.S.S.N. 62/196,253, filed Jul. 23, 2015, entitled “EVOLUTION OF BT TOXINS,” and U.S.S.N. 62/305,497, filed Mar. 8, 2016, entitled “EVOLUTION OF BT TOXINS,” each of which is incorporated herein by reference.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under grant numbers HR0011-11-2-0003 and N66001-12-C-4207 awarded by the Defense Advanced Research Projects Agency (DARPA). The government has certain rights in the invention.

REFERENCE TO AN ELECTRONIC SEQUENCE LISTING

[0003] The contents of the electronic sequence listing (H082470187US04-SEQ-CBD.xml; Size: 15,862 bytes; and Date of Creation: Oct. 14, 2022) is herein incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

[0004] *Bacillus thuringiensis* (Bt) is a gram-positive bacterium that produces crystalline inclusion bodies (Bt toxins) during sporulation, which exhibit potent insecticidal activity through disruption of the osmotic balance in the insect midgut as a consequence of membrane insertion and pore formation (FIG. 1). A limited number of Bt toxins have become widespread biological alternatives to chemical insecticides. Bt toxins can be delivered to insect pests via conventional application routes, and can also be produced in the plant at all times during the plant life cycle to protect the plant from infestation. Bt toxins are benign to other arthropods within the crop field as well as to humans, and are environmentally friendly. However, the development of resistance to this limited set of Bt toxins in some targeted pests represents a serious threat to the viability of these and related Bt toxins for use in pest control applications. Thus there is a need for the development of pesticidal toxin molecules that can be produced in or applied to plants and seeds, that can control targeted pests that have developed resistance to one or more toxin proteins.

SUMMARY OF THE INVENTION

[0005] The Bt toxin Cry1Ac has been widely used in plants for the past two decades to control certain lepidopteran species of insect pests. Some target pests have developed resistance to this and to related Bt toxins, and resistant populations of pests have become a problematic phenomenon. Thus, there is a need for the development of novel Bt toxins that are effective against pests that have developed resistance to currently available Bt toxins.

[0006] Some aspects of the present disclosure are based on the recognition that methods of phage-assisted continuous evolution (PACE) are useful for generating variant polypeptides based on Bt toxins that exhibit altered Bt toxin receptor

binding capabilities. Such variant polypeptides comprising altered amino acid sequences as compared to wild-type Bt toxins, referred to herein as variant Bt toxins or Bt toxin variants, hold the potential to exhibit efficacy against a variety of target pests. Some aspects of this disclosure provide variant Bt toxins that bind with higher affinity to a receptor in a Bt toxin-resistant pest than the wild-type Bt toxin.

[0007] The general concept of PACE technology been described, for example in International PCT Application, PCT/US2009/056194, filed Sep. 8, 2009, published as WO 2010/028347 on Mar. 11, 2010; International PCT Application, PCT/US2011/066747, filed Dec. 22, 2011, published as WO 2012/088381 on Jun. 28, 2012; and U.S. Application, U.S.S.N. 13/922,812, filed Jun. 20, 2013, the entire contents of each of which are incorporated herein by reference.

[0008] Some aspects of this disclosure relate to variant Bt toxins and methods for producing the same. In some aspects, the disclosure provides a protein comprising an amino acid sequence that is at least 70%, at least 80%, at least 90%, at least 95%, at least 96%, at least 97%, at least 98%, or at least 99% identical to SEQ ID NO: 1 (protein encoded by *B. thuringiensis* Cry1Ac; GenBank Accession No. AY730621, residues 2-609), wherein the protein comprises at least one amino acid variation (also referred to sometimes as “mutation”) in the amino acid sequence provided in Table 1. In some embodiments, the amino acid sequence is at least 75%, at least 85%, at least 95%, at least 96%, at least 97%, at least 98%, at least 99%, at least 99.5%, at least 99.6%, at least 99.7%, at least 99.8%, or at least 99.9% identical to SEQ ID NO: 1. In some embodiments, the amino acid sequence is about 95-99.9% identical to SEQ ID NO: 1. In some embodiments, the protein comprises at least 2, at least 3, at least 4, at least 5, at least 6, at least 7, at least 8, at least 9, at least 10, at least 11, at least 12, at least 13, at least 14, or at least 15 different amino acid sequence variations provided in Table 1 as compared to the sequence of amino acids set forth in SEQ ID NO:1. In some embodiments, the at least one variation in sequence is located in a portion of the receptor binding domain of the protein (e.g., in a sequence corresponding to amino acid residues 275-462 of SEQ ID NO: 1). In some embodiments, there is at least one variation in amino acid sequence of the protein that is selected from the group consisting of: C14W, C14R, F67S, R197G, A267T, T303N, M321K, E331G, A343E, Q352H, T360I, S362P, N416D, E460K, N462S, D383Y, S403C, and S581L. In some embodiments, the protein does not comprise a destabilizing mutation/variation in the amino acid sequence of the protein, e.g., a mutation that increases the proteins’ sensitivity to tryptic digest or to thermal variation, as compared to the wild-type Bt toxin (e.g., to a Bt toxin having the amino acid sequence of SEQ ID NO: 1). In some embodiments, the protein does not comprise a variation in protein sequence at the residue corresponding to residue D383 of SEQ ID NO: 1 and/or at the residue corresponding to residue S403 of SEQ ID NO: 1. In some embodiments, the protein comprises the wild-type amino acid at the residue corresponding to D383 of SEQ ID NO: 1 and/or at the residue corresponding to residue S403 of SEQ ID NO: 1. In some embodiments, the protein comprises the mutations E460K, N462S, T303N, A343E, T360I, S581L, C14W, M321K, and Q352H. In some embodiments, the protein comprises the mutations E460K, N462S, T303N, A343E, T360I, S581L, C14W, M321K, Q352H, F67S,

G285D, and E331G. In some embodiments, the protein comprises the mutations E460K, N462S, T303N, A343E, T360I, S581L, C14W, M321K, Q352H, F67S, G285D, and E331G.

[0009] In some aspects, the disclosure provides a protein comprising a receptor binding domain, wherein the receptor binding domain comprises an amino acid sequence that is at least 70%, at least 80%, at least 85%, at least 90%, at least about 94%, at least 95%, at least 96%, at least 97%, at least 98%, at least 99%, or at least 99.4% identical to amino acid residues 275-462 of SEQ ID NO: 1, wherein the receptor binding domain comprises at least one variation in protein sequence provided in Table 1, and wherein the protein binds a Bt toxin receptor with higher affinity than SEQ ID NO: 1. In some embodiments, the receptor binding domain comprises an amino acid sequence that is at least 70%, at least 80%, at least 85%, at least 90%, at least 92%, at least 93%, at least 94%, at least 95%, at least 96%, at least 97%, at least 98%, at least 99%, or at least 99.9% identical to the receptor binding domain as set forth in SEQ ID NO: 1 from amino acid residues 275-462. In some embodiments, the receptor binding domain comprises an amino acid sequence having at least 2, at least 3, at least 4, at least 5, at least 6, at least 7, at least 8, at least 9, at least 10, at least 11, at least 12, at least 13, at least 14, or at least 15 mutations provided in Table 1. In some embodiments, the at least one variation in amino acid sequence of the protein is selected from the group consisting of: T303N, M321K, E331G, A343E, Q352H, T360I, S362P, N416D, E460K, and N462S. In some embodiments, the protein does not comprise a destabilizing variation in amino acid sequence of the protein, e.g., a mutation that reduces the stability of the protein against tryptic digest or increases or decreases thermal stability as compared to the wild-type Bt toxin (e.g., to a Bt toxin having the amino acid sequence of SEQ ID NO: 1). In some embodiments, the protein does not comprise a mutation at the residue corresponding to residue D383 of SEQ ID NO: 1 and/or at the residue corresponding to residue S403 of SEQ ID NO: 1. In some embodiments, the protein comprises the wild-type amino acid at the residue corresponding to D383 of SEQ ID NO: 1 and/or at the residue corresponding to residue S403 of SEQ ID NO: 1. In some embodiments, the protein comprises the variation in amino acid sequence E460K, N462S, T303N, A343E, T360I, M321K, and Q352H. In some embodiments, the protein comprises the variation in amino acid sequence E460K, N462S, T303N, A343E, T360I, M321K, Q352H, G285D, and E331G. In some embodiments, the protein binds to a Bt toxin receptor comprising an amino acid sequence represented by SEQ ID NO: 2 (*Trichoplusia ni* cadherin, GenBank Accession No. AEA29692, residues 1133-1582).

[0010] In some embodiments, the protein is effective in killing insects that are resistant to treatment with Bt toxin, e.g., resistant to treatment with a protein represented by SEQ ID NO: 1. In some embodiments, the insects are selected from the group consisting of the orders *Lepidoptera*, *Coleoptera*, *Diptera*, and *Hemiptera*.

[0011] In some aspects, the disclosure provides a genetically engineered cell expressing a variant Bt toxin from a recombinant nucleotide sequence operably linked to a promoter functional in said cell. The nucleotide sequence encodes the protein as described herein. In some embodiments, the cell is a bacterial cell. In some embodiments, the bacterial cell is an *E. coli* cell. In some embodiments,

the cell is a plant cell. In some embodiments, the plant cell is a monocot plant cell or a dicot plant cell. For example, dicot plant cells and dicot plants derived therefrom may include but are not limited to tomato, cotton, sugar beet, potato, soybean, tobacco, canola, and alfalfa. Monocot plant cells and monocot plants derived therefrom may include but are not limited to corn, sugarcane, wheat, and rice.

[0012] In some aspects, the disclosure provides a genetically modified plant, wherein the plant comprises or consists of recombinant plant cells expressing a pesticidal toxin as provided herein. In some embodiments, the plant is a monocot plant or a dicot plant as noted above. In some embodiments, the plant is resistant to pest infestation by one or more pests that previously were not inhibited by pesticidal proteins or by Bt toxins.

[0013] In some aspects, the disclosure provides a method for producing an evolved pesticidal toxin protein, the method comprising: (a) contacting a population of bacterial host cells with a population of M13 phages comprising a first gene encoding a first fusion protein, and deficient in a full-length pIII gene, wherein (1) the first fusion protein comprises a pesticidal toxin protein binding region (TBR) and a repressor element, (2) the phage allows for expression of the first fusion protein in the host cells, (3) the host cells are suitable host cells for M13 phage infection, replication, and packaging; and (4) the host cells comprise an expression construct comprising a second gene encoding the full length pIII protein and a third gene encoding a second fusion protein comprising a pesticidal toxin and an RNA polymerase, wherein expression of the gene encoding the full length pIII is dependent on interaction of the RNA polymerase of the second fusion protein with the TBR of the first fusion protein; (b) incubating the population of host cells under conditions allowing for mutations (and thus, amino acid substitutions) to be introduced into the third gene, the production of infectious M13 phage, and the infection of host cells with M13 phage, wherein infected cells are removed from the population of host cells, and wherein the population of host cells is replenished with fresh host cells that are not infected by M13 phage; and, (c) isolating a mutated M13 phage replication product encoding an evolved second fusion protein from the population of host cells. In some embodiments, the host cells further comprise a mutagenesis plasmid. In some embodiments, the mutagenesis plasmid is an MP4 or MP6 plasmid. In some embodiments, the pesticidal toxin is Cry1Ac (SEQ ID NO: 1), or a fragment thereof. In some embodiments, the fragment of Cry1Ac comprises the receptor binding domain. In some embodiments, the RNA polymerase is RpoZ or RpoA. In some embodiments, the expression construct encoding the full length pIII protein further comprises a promoter. In some embodiments, the promoter is a lacZ promoter or a mutant lacZ promoter. In some embodiments, the expression construct encoding the full length pIII protein further comprises a repressor binding site. In some embodiments, the repressor binding site is a lambda phage (λ) cI, 434 cI, or Zif268 binding site. In some aspects, the disclosure relates to a method of pest control, the method comprising, providing to a pest a pesticidal toxin variant as described by the disclosure. In some embodiments, the pest is selected from the group consisting of the Orders *Lepidoptera*, *Coleoptera*, *Diptera*, and *Hemiptera*. In some embodiments, the pest is resistant to

treatment with the pesticidal toxin, wherein the pesticidal toxin is represented by SEQ ID NO: 1.

[0014] The summary above is meant to illustrate, in a non-limiting manner, some of the embodiments, advantages, features, and uses of the technology disclosed herein. Other embodiments, advantages, features, and uses of the technology disclosed herein will be apparent from the Detailed Description, the Drawings, the Examples, and the Claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 shows a schematic illustration of Bt toxin mechanisms of action.

[0016] FIGS. 2A-2C show schematic illustrations of cadherin-like receptors from *T. ni* and other insect species (*B. mori*, *H. amigera*, *H. viscerens*, *M. sexta*). Partial amino acid sequences for each cadherin-like receptor are depicted, along with the consensus TBR3 amino acid sequence. In FIG. 2A, the sequences from top to bottom correspond to SEQ ID NOs: 7-11.

[0017] FIG. 3 shows a schematic illustration of the PACE evolution strategy for evolving enhanced Bt toxin variants.

[0018] FIGS. 4A-4B describe Round 1 of PACE selection of Cry1Ac variants. The low stringency/moderate mutagenesis B2H system is graphically depicted. Mutagenesis plasmid M4 is shown as a vector map. Data on the histogram represent 132 hours of PACE. Consensus mutations of Cry1Ac are located in the receptor binding domain (Domain II).

[0019] FIGS. 5A-5B describe Round 2 of PACE selection of Cry1Ac variants. The intermediate stringency/moderate mutagenesis B2H system is graphically depicted. Mutagenesis plasmid M4 is shown as a vector map. Data on the histogram represent 264 hours of PACE.

[0020] FIGS. 6A-6B describe Round 3 of PACE selection of Cry1Ac variants. The intermediate stringency/high mutagenesis B2H system is graphically depicted. Mutagenesis plasmid M6 is shown as a vector map. Data on the histogram represent 384 hours of PACE. The pool converged on the majority of the Cry1Ac mutations depicted.

[0021] FIGS. 7A-7B describe Round 4 of PACE selection of Cry1Ac variants. The high stringency/high mutagenesis B2H system is graphically depicted. Mutagenesis plasmid M6 is shown as a vector map. Data on the histogram represent 528 hours of PACE. Four additional convergent mutations resulted from this round of PACE.

[0022] FIGS. 8A-8B illustrate PACE evolution assay data. FIG. 8A illustrates phage titer, lagoon flow rate, and average mutations per clone in the four-round PACE evolution assay. FIG. 8B illustrates examples of mutations identified in the four-round PACE evolution assay.

[0023] FIGS. 9A-9C illustrate mutations observed during the four-round PACE evolution assay.

[0024] FIG. 10 shows protein SDS gel electrophoresis of trypsin treated protein samples corresponding to Cry1Ac1 and variants thereof (upper panel). The arrow indicates the band of the toxic core. EV: Empty vector control; DM: Double mutant Cry1Ac1_D383Y_S403C. Center panel shows the amino acid substitutions of the PACE variants tested in the upper panel. Amino acid numbering corresponds to SEQ ID NO: 1. Bottom panel shows protein SDS gel electrophoresis of trypsin treated protein samples corresponding to selected stabilized variants. The arrow indicates the band of the toxic core.

[0025] FIG. 11 shows PACE-evolved Cry1Ac variant activity in Sf9 cells. PACE-evolved Cry1Ac variants are active against *T. ni* cadherin-like receptor CAD3 expressed in Sf9 cells. Wild-type Cry1Ac is inactive.

[0026] FIG. 12 shows PACE-evolved Cry1Ac variant activity in *T. ni* larvae. PACE-evolved Cry1Ac variants are active against soybean looper in a diet bioassay but efficacy is lower than wild-type Cry1Ac.

[0027] FIG. 13 shows data from a melting assay with purified "stabilization" consensus PACE-evolved Cry1Ac1 variants.

[0028] FIGS. 14A-14C show PACE-evolved Cry1Ac variant binding affinity for *T. ni* cadherin-like receptor. PACE-evolved Cry1Ac variant binds to the receptor with high affinity; wild-type Cry1Ac does not bind to the receptor. The lower panel shows in vitro binding of purified stabilized consensus PACE-evolved Cry1Ac1 variants to toxin-binding domain TBR3 from the *T. ni* cadherin, immobilized on a ForteBio chip via His-tag.

[0029] FIG. 15 shows screening of Cry1Ac1 variants (solubilized and trypsinized Bt spore/crystal mixtures) for toxicity to Sf9 cells expressing *T. ni* cadherin expressed as relative fluorescence caused by influx of SytoxGreen fluorescent dye into cells as result of toxin-induced membrane disruption.

[0030] FIG. 16 shows toxicity of purified Cry1Ac1 consensus Cry1Ac1 PACE-evolved variant Cry1Ac1_C03 and stabilized consensus Cry1Ac1 PACE-evolved variants (at 10 µg/ml), to Sf9 cells expressing *C. includens* cadherin.

[0031] FIG. 17 shows the activity of stabilized Cry1Ac1 variants (Bt spore/crystal mixtures) against soybean looper (*C. includens*). Numbers above bars are stunting scores. Letters below bars are for mortality T-grouping for mortality.

[0032] FIG. 18 shows the activity (mortality) of stabilized consensus PACE-evolved Cry1Ac1 variants (Bt spore/crystal mixtures) in diet bioassay against *T. ni*. Numbers above bars are stunting scores (maximum stunting score - 3). Letters below bars are for mortality T-grouping.

[0033] FIG. 19 shows data from a larval growth inhibition assay in Bt toxin susceptible and Bt toxin resistant *T. ni*. The larvae were exposed to wild-type Cry1Ac (control) and to various evolved Bt toxins. The data demonstrate that exemplary stabilized evolved Bt toxins are efficient against both *T. ni* larvae that are susceptible to wild-type Bt toxin and *T. ni* larvae that are resistant to wild-type Bt Toxin.

[0034] FIG. 20A-20C show oligotyping analysis of lagoon samples during PACE based on high-throughput DNA sequencing data. FIG. 20A shows oligotypes containing mutations that occur at high frequency ($\geq 1\%$) which are represented by different polygons in the graph, shaded based on the stage in which they first became abundant in the evolving Cry1Ac gene pool. FIG. 20B shows the genotype of each oligotype in the table. The numbers in parentheses indicate the oligotype number assigned to that mutant following a synonymous (silent) mutation. FIG. 20C illustrates plausible evolution trajectories over the entire PACE experiment derived from oligotyping analysis which indicates instances of recombination during PACE, and also reveals the influence of mutation rate, selection stringency, and target protein on evolutionary outcomes.

[0035] FIGS. 21A-21D show insect diet bioassay activity of PACE-evolved Cry1Ac variants against various agricultural pests. Two consensus and three stabilized PACE-evolved Cry1Ac variants were tested for activity in eleven

pests: *Chrysodeixis includes* (soybean looper); *Heliothis virescens* (tobacco budworm); *Helicoverpa zea* (corn earworm); *Plutella xylostella* (diamondback moth); *Agrotis ipsilon* (black cutworm); *Spodoptera frugiperda* (fall armyworm); *Anticarsia gemmatilis* (velvetbean caterpillar); *Diatraea saccharalis* (sugarcane borer); *Spodoptera eridania* (southern armyworm); *Leptinotarsa decemlineata* (Colorado potato beetle); and *Lygus lineolaris* (tarnished plant bug). Stabilized variants showed enhanced activity in *C. includes* and *H. virescens* as compared to wild-type Cry1Ac, and comparable activity to wild-type Cry1Ac in *H. zea*, *P. xylostella*, *A. ipsilon*, *S. frugiperda*, *A. gemmatilis*, and *D. saccharalis*. No activity was observed for any of the Cry1Ac variants at any tested dose for *S. eridania*, *L. decemlineata* or *L. lineolaris*. No insect larvae mortality was observed for *S. frugiperda*, although high toxin doses greatly stunted growth.

[0036] FIG. 22 shows comparison of cadherin receptor sequence identity. The % sequence identity using the full-length cadherin receptor (top) or fragment used for directed evolution experiments (bottom) for insects tested in FIG. 21. Numbers in parenthesis denote the number of identical amino acids between the two receptors. Mortality and stunting data from diet bioassays correlates with cadherin receptor sequence identity.

DEFINITIONS

Bacillus Thuringiensis (Bt) Toxins

[0037] The term “Bt toxin,” as used herein, refers to a pesticidal toxin or pesticidal protein that achieves its pesticidal effect(s) upon a target pest by physically interacting with one or more proteins present within and produced by that target pest. In some embodiments, the term “Bt toxin” refers to one or more proteins (e.g., crystal (Cry) protein(s)) that are produced by *Bacillus thuringiensis*, or a subspecies thereof (e.g., *B. thuringiensis kurstaki*, *B. thuringiensis israeliensis*, or *B. thuringiensis aizawa*). Exemplary Bt toxins encoded by a cry gene include: Cry1Aa1-Cry1Aa23, Cry1Ab1-Cry1Ab34, and Cry1Ac1-Cry1Ac38. Other Bt toxins are known in the art, for example those disclosed in Crickmore et al., Revision of the Nomenclature for the *Bacillus thuringiensis* Pesticidal Crystal Proteins, Microbiology and Molecular Biology Reviews (1998) Vol 62: 807-813. A listing of Bt toxins derived from *Bacillus thuringiensis* and related species of bacteria can be found as of the filing date of this application on the world wide web at lifesci.sussex.ac.uk/home/Neil_Crickmore/Bt/index.html. Generally, pesticidal toxins are useful as insecticides against species within the insect Orders *Lepidoptera*, *Coleoptera*, *Hemiptera* and *Diptera*, and also as nematicides against plant pathogenic nematodes. Genetically modified plants that express one or more Bt toxins are known in the art.

[0038] The term “Bt toxin variant,” as used herein, refers to a Bt toxin protein having one or more amino acid variations introduced into the amino acid sequence, e.g., as a result of application of the PACE method, as compared to the amino acid sequence of a naturally-occurring or wild-type pesticidal toxin. Amino acid sequence variations may include one or more mutated residues within the amino acid sequence of the toxin, e.g., as a result of a change in the nucleotide sequence encoding the toxin that results in a change in the codon at any particular position in the coding

sequence, the deletion of one or more amino acids (e.g., a truncated protein), the insertion of one or more amino acids, or any combination of the foregoing.

[0039] A wild-type Bt toxin refers to the amino acid sequence of a Bt toxin as it naturally occurs in a *Bacillus thuringiensis* genome. An example of a wild-type Bt toxin is the Cry1Ac protein, which is represented by the amino acid sequence set forth in SEQ ID NO: 1.

[0040] The term “receptor binding domain,” as used herein refers to the portion of the Bt toxin that interacts with a target receptor. Generally, the target receptor is located on a target cell membrane. Several insect cell surface receptors are known to interact with certain Bt toxins, including cadherin-like proteins (CADR), glycosyl-phosphatidyl-inositol (GPI)-anchored aminopeptidase-N (APN), GPI-anchored alkaline phosphatase (ALP) and a 270 kDa glycol-conjugate, however, no single Bt toxin has been shown to interact with more than one of these receptor proteins. For most Bt toxins, the specific receptor that is the target for binding in a target insect species is not known.

[0041] Many Bt toxins are comprised of three distinct structural domains, and the ligand (receptor) binding domain of any particular Bt toxin usually is made up of the exposed regions (solvent accessible regions) of the second and third structural domains, commonly referred to as domain II and domain III.

[0042] The term “toxin binding region (TBR),” refers to the epitope or epitopes of a target pest protein (commonly referred to as a receptor) that, when exposed to a pesticidal protein that exhibits toxic effects upon the target pest, interacts with the pesticidal protein. Generally, a TBR of any particular insect protein that functions as such a receptor comprises several amino acid residues that interact with a pesticidal protein. A toxin binding region can comprise several (e.g., 1, 2, 3, 4, or more) epitopes (e.g., residues) that bind to Bt toxin.

[0043] The term “higher affinity,” as used herein, with respect to any particular receptor protein, refers to the increased binding strength of a first protein relative to the binding strength of a second protein, for example, under conditions in which both the first and second protein interact with and bind to the receptor. For example, if protein A has a binding affinity of 1X Kd to receptor Y and protein B has a binding affinity of 3X Kd to receptor Y, then protein A binds to receptor Y with higher affinity than protein B.

Continuous Evolution

[0044] The term “continuous evolution,” as used herein, refers to an evolution procedure, in which a population of nucleic acids is subjected to multiple rounds of (a) replication, (b) mutation (or modification of the primary sequence of nucleotides of the nucleic acids in the population), and (c) selection to produce a desired evolved product, for example, a novel nucleic acid encoding a novel protein with a desired activity, wherein the multiple rounds of replication, mutation and selection can be performed without investigator interaction and wherein the processes under (a)-(c) can be carried out simultaneously. Typically, the evolution procedure is carried out in vitro, for example, using cells in culture as host cells. In general, a continuous evolution process provided herein relies on a system in which a gene of interest is provided in a nucleic acid vector that undergoes a life-cycle including replication in a host cell and transfer to

another host cell, wherein a critical component of the life-cycle is deactivated and reactivation of the component is dependent upon a desired variation in amino acid sequence of a protein encoded by the gene of interest.

[0045] In some embodiments, the gene of interest is transferred from cell to cell in a manner dependent on the activity of the gene of interest. In some embodiments, the transfer vector is a virus infecting cells, for example, a bacteriophage, or a retroviral vector. In some embodiments, the viral vector is a phage vector infecting bacterial host cells. In some embodiments, the transfer vector is a conjugative plasmid transferred from a donor bacterial cell to a recipient bacterial cell.

[0046] In some embodiments, the nucleic acid vector comprising the gene of interest is a phage, a viral vector, or naked DNA (e.g., a mobilization plasmid). In some embodiments, transfer of the gene of interest from cell to cell is via infection, transfection, transduction, conjugation, or uptake of naked DNA, and efficiency of cell-to-cell transfer (e.g., transfer rate) is dependent on an activity of a product encoded by the gene of interest. For example, in some embodiments, the nucleic acid vector is a phage harboring the gene of interest and the efficiency of phage transfer (via infection) is dependent on an activity of the gene of interest in that a protein required for the generation of phage particles (e.g., pIII for M13 phage) is expressed in the host cells only in the presence of the desired activity of the gene of interest.

[0047] For example, some embodiments provide a continuous evolution system, in which a population of viral vectors comprising a gene of interest to be evolved replicates in a flow of host cells, e.g., a flow through a lagoon, wherein the viral vectors are deficient in a gene encoding a protein that is essential for the generation of infectious viral particles, and wherein that gene is comprised in the host cell under the control of a conditional promoter that can be activated by a gene product encoded by the gene of interest, or a mutated version thereof. In some embodiments, the activity of the conditional promoter depends on a desired function of a gene product encoded by the gene of interest. Viral vectors, in which the gene of interest has not acquired a desired function as a result of a variation of amino acids introduced into the gene product protein sequence, will not activate the conditional promoter, or may only achieve minimal activation, while any mutations introduced into the gene of interest that confers the desired function will result in activation of the conditional promoter. Since the conditional promoter controls an essential protein for the viral life cycle, e.g., pIII, activation of this promoter directly corresponds to an advantage in viral spread and replication for those vectors that have acquired an advantageous mutation.

[0048] The term “flow,” as used herein in the context of host cells, refers to a stream of host cells, wherein fresh host cells are being introduced into a host cell population, for example, a host cell population in a lagoon, remain within the population for a limited time, and are then removed from the host cell population. In a simple form, a host cell flow may be a flow through a tube, or a channel, for example, at a controlled rate. In other embodiments, a flow of host cells is directed through a lagoon that holds a volume of cell culture media and comprises an inflow and an outflow. The introduction of fresh host cells may be continuous or intermittent and removal may be passive, e.g., by overflow, or active, e.g., by active siphoning or pumping. Removal further

may be random, for example, if a stirred suspension culture of host cells is provided, removed liquid culture media will contain freshly introduced host cells as well as cells that have been a member of the host cell population within the lagoon for some time. Even though, in theory, a cell could escape removal from the lagoon indefinitely, the average host cell will remain only for a limited period of time within the lagoon, which is determined mainly by the flow rate of the culture media (and suspended cells) through the lagoon.

[0049] Since the viral vectors replicate in a flow of host cells, in which fresh, uninfected host cells are provided while infected cells are removed, multiple consecutive viral life cycles can occur without investigator interaction, which allows for the accumulation of multiple advantageous mutations in a single evolution experiment.

[0050] The term “phage-assisted continuous evolution (PACE),” as used herein, refers to continuous evolution that employs phage as viral vectors.

Viral Vectors

[0051] The term “viral vector,” as used herein, refers to a nucleic acid comprising a viral genome that, when introduced into a suitable host cell, can be replicated and packaged into viral particles able to transfer the viral genome into another host cell. The term viral vector extends to vectors comprising truncated or partial viral genomes. For example, in some embodiments, a viral vector is provided that lacks a gene encoding a protein essential for the generation of infectious viral particles. In suitable host cells, for example, host cells comprising the lacking gene under the control of a conditional promoter, however, such truncated viral vectors can replicate and generate viral particles able to transfer the truncated viral genome into another host cell. In some embodiments, the viral vector is a phage, for example, a filamentous phage (e.g., an M13 phage). In some embodiments, a viral vector, for example, a phage vector, is provided that comprises a gene of interest to be evolved.

[0052] The term “nucleic acid,” as used herein, refers to a polymer of nucleotides. The polymer may include natural nucleosides (i.e., adenosine, thymidine, guanosine, cytidine, uridine, deoxyadenosine, deoxythymidine, deoxyguanosine, and deoxycytidine), nucleoside analogs (e.g., 2-aminoadenosine, 2-thiothymidine, inosine, pyrrolo-pyrimidine, 3-methyl adenosine, 5-methylcytidine, C5-bromouridine, C5-fluorouridine, C5-iodouridine, C5-propynyl-uridine, C5-propynyl-cytidine, C5-methylcytidine, 7-deazaadenosine, 7-deazaguanosine, 8-oxoadenosine, 8-oxoguanosine, O(6)-methylguanine, 4-acetylcytidine, 5-(carboxyhydroxymethyl)uridine, dihydrouridine, methylpseudouridine, 1-methyl adenosine, 1-methyl guanosine, N6-methyl adenosine, and 2-thiocytidine), chemically modified bases, biologically modified bases (e.g., methylated bases), intercalated bases, modified sugars (e.g., 2'-fluororibose, ribose, 2'-deoxyribose, 2'-O-methylcytidine, arabinose, and hexose), or modified phosphate groups (e.g., phosphorothioates and 5'—N—phosphoramidite linkages).

[0053] The term “protein,” as used herein refers to a polymer of amino acid residues linked together by peptide bonds. The term, as used herein, refers to proteins, polypeptides, and peptide of any size, structure, or function. Typically, a protein will be at least three amino acids long. A protein may refer to an individual protein or a collection of proteins. Inventive proteins preferably contain only natural

amino acids, although non-natural amino acids (i.e., compounds that do not occur in nature but that can be incorporated into a polypeptide chain; see, for example, cco.caltech.edu/~dadgrp/Unnatstruct.gif on the world wide web, which displays structures of non-natural amino acids that have been successfully incorporated into functional ion channels) and/or amino acid analogs as are known in the art may alternatively be employed. Also, one or more of the amino acids in an inventive protein (e.g., a Bt toxin) may be modified, for example, by the addition of a chemical entity such as a carbohydrate group, a hydroxyl group, a phosphate group, a farnesyl group, an isofarnesyl group, a fatty acid group, a linker for conjugation, functionalization, or other modification, etc. A protein may also be a single molecule or may be a multi-molecular complex. A protein may be just a fragment of a naturally occurring protein or peptide. A protein may be naturally occurring, recombinant, or synthetic, or any combination of these.

[0054] The term “gene of interest,” as used herein, refers to a nucleic acid construct comprising a nucleotide sequence encoding a gene product (e.g., a protein) of interest, for example, a gene product to be evolved in a continuous evolution process as provided herein. The term includes any variations of a gene of interest that are the result of a continuous evolution process according to methods provided herein. For example, in some embodiments, a gene of interest is a nucleic acid construct comprising a nucleotide sequence encoding a protein to be evolved (e.g., a Bt toxin), cloned into a viral vector, for example, a phage genome, so that the expression of the encoding sequence is under the control of one or more promoters in the viral genome. In other embodiments, a gene of interest is a nucleic acid construct comprising a nucleotide sequence encoding a protein to be evolved and a promoter operably linked to the encoding sequence. For example, a gene of interest encoding a Bt toxin to be evolved may be expressed in host cells, wherein the evolution of the Bt toxin is dependent upon the interaction of the Bt toxin with a second protein expressed from an accessory plasmid of a viral vector (e.g., the TBR of a Bt toxin receptor expressed by an M13 phage). When cloned into a viral vector, for example, a phage genome, the expression of the encoding sequence of such genes of interest is under the control of the heterologous promoter and, in some embodiments, may also be influenced by one or more promoters comprised in the viral genome.

[0055] The term “function of a gene of interest,” as interchangeably used with the term “activity of a gene of interest,” refers to a function or activity of a gene product, for example, a nucleic acid, or a protein, encoded by the gene of interest. For example, a function of a gene of interest may be an enzymatic activity (e.g., an enzymatic activity resulting in the generation of a reaction product, phosphorylation activity, phosphatase activity, etc.), an ability to activate transcription (e.g., transcriptional activation activity targeted to a specific promoter sequence), a bond-forming activity, (e.g., an enzymatic activity resulting in the formation of a covalent bond), or a binding activity (e.g., a protein, DNA, or RNA binding activity).

[0056] The term “promoter” refers to a nucleic acid molecule with a sequence recognized by the cellular transcription machinery and able to initiate transcription of a downstream gene. Typically, a promoter is A promoter can be constitutively active, meaning that the promoter is always active in a given cellular context, or conditionally active, meaning that

the promoter is only active under specific conditions. For example, a conditional promoter may only be active in the presence of a specific protein that connects a protein associated with a regulatory element in the promoter to the basic transcriptional machinery, or only in the absence of an inhibitory molecule. A subclass of conditionally active promoters are inducible promoters that require the presence of a small molecule “inducer” for activity. Examples of inducible promoters include, but are not limited to, arabinose-inducible promoters, Tet-on promoters, and tamoxifen-inducible promoters. A variety of constitutive, conditional, and inducible promoters are well known to the skilled artisan, and the skilled artisan will be able to ascertain a variety of such promoters useful in carrying out the instant invention, which is not limited in this respect.

[0057] The term “viral particle,” as used herein, refers to a viral genome, for example, a DNA or RNA genome, that is associated with a coat of a viral protein or proteins, and, in some cases, with an envelope of lipids. For example, a phage particle comprises a phage genome packaged into a protein encoded by the wild type phage genome.

[0058] The term “infectious viral particle,” as used herein, refers to a viral particle able to transport the viral genome it comprises into a suitable host cell. Not all viral particles are able to transfer the viral genome to a suitable host cell. Particles unable to accomplish this are referred to as non-infectious viral particles. In some embodiments, a viral particle comprises a plurality of different coat proteins, wherein one or some of the coat proteins can be omitted without compromising the structure of the viral particle. In some embodiments, a viral particle is provided in which at least one coat protein cannot be omitted without the loss of infectivity. If a viral particle lacks a protein that confers infectivity, the viral particle is not infectious. For example, an M13 phage particle that comprises a phage genome packaged in a coat of phage proteins (e.g., pVIII) but lacks pIII (protein III) is a non-infectious M13 phage particle because pIII is essential for the infectious properties of M13 phage particles.

[0059] The term “viral life cycle,” as used herein, refers to the viral reproduction cycle comprising insertion of the viral genome into a host cell, replication of the viral genome in the host cell, and packaging of a replication product of the viral genome into a viral particle by the host cell.

[0060] In some embodiments, the viral vector provided is a phage. The term “phage,” as used herein interchangeably with the term “bacteriophage,” refers to a virus that infects bacterial cells. Typically, phages consist of an outer protein capsid enclosing genetic material. The genetic material can be ssRNA, dsRNA, ssDNA, or dsDNA, in either linear or circular form. Phages and phage vectors are well known to those of skill in the art and non-limiting examples of phages that are useful for carrying out the methods provided herein are λ (Lysogen), T2, T4, T7, T12, R17, M13, MS2, G4, P1, P2, P4, Phi X174, N4, Φ 6, and Φ 29. In certain embodiments, the phage utilized in the present invention is M13. Additional suitable phages and host cells will be apparent to those of skill in the art and the invention is not limited in this aspect. For an exemplary description of additional suitable phages and host cells, see Elizabeth Kutter and Alexander Sulakvelidze: *Bacteriophages: Biology and Applications*. CRC Press; 1st edition (December 2004), ISBN: 0849313368; Martha R. J. Clokie and Andrew M. Kropinski: *Bacteriophages: Methods and Protocols, Volume 1: Isolation, Characterization, and Interactions (Methods in*

Molecular Biology) Humana Press; 1st edition (December, 2008), ISBN: 1588296822; Martha R. J. Clokie and Andrew M. Kropinski: *Bacteriophages: Methods and Protocols, Volume 2: Molecular and Applied Aspects (Methods in Molecular Biology)* Humana Press; 1st edition (December 2008), ISBN: 1603275649; all of which are incorporated herein in their entirety by reference for disclosure of suitable phages and host cells as well as methods and protocols for isolation, culture, and manipulation of such phages).

[0061] In some embodiments, the phage is a filamentous phage. In some embodiments, the phage is an M13 phage. M13 phages are well known to those in the art and the biology of M13 phages has extensively been studied. Wild type M13 phage particles comprise a circular, single-stranded genome of approximately 6.4 kb. In certain embodiments, the wild-type genome of an M13 phage includes eleven genes, gI-gXI, which, in turn, encode the eleven M13 proteins, pI-pXI, respectively. gVIII encodes pVIII, also often referred to as the major structural protein of the phage particles, while gIII encodes pIII, also referred to as the minor coat protein, which is required for infectivity of M13 phage particles.

[0062] The M13 life cycle includes attachment of the phage to the sex pilus of a suitable bacterial host cell via the pIII protein and insertion of the phage genome into the host cell. The circular, single-stranded phage genome is then converted to a circular, double-stranded DNA, also termed the replicative form (RF), from which phage gene transcription is initiated. The wild type M13 genome comprises nine promoters and two transcriptional terminators as well as an origin of replication. This series of promoters provides a gradient of transcription such that the genes nearest the two transcriptional terminators (gVIII and IV) are transcribed at the highest levels. In wild-type M13 phage, transcription of all 11 genes proceeds in the same direction. One of the phage-encode proteins, pII, initiates the generation of linear, single-stranded phage genomes in the host cells, which are subsequently circularized, and bound and stabilized by pV. The circularized, single-stranded M13 genomes are then bound by pVIII, while pV is stripped off the genome, which initiates the packaging process. At the end of the packaging process, multiple copies of pIII are attached to wild-type M13 particles, thus generating infectious phage ready to infect another host cell and concluding the life cycle.

[0063] The M13 phage genome can be manipulated, for example, by deleting one or more of the wild type genes, and/or inserting a heterologous nucleic acid construct into the genome. M13 does not have stringent genome size restrictions, and insertions of up to 42 kb have been reported. This allows M13 phage vectors to be used in continuous evolution experiments to evolve genes of interest without imposing a limitation on the length of the gene to be involved.

[0064] The term “selection phage,” as used herein interchangeably with the term “selection plasmid,” refers to a modified phage that comprises a gene of interest to be evolved and lacks a full-length gene encoding a protein required for the generation of infective phage particles. For example, some M13 selection phage provided herein comprise a nucleic acid sequence encoding a protein to be evolved, e.g., under the control of an M13 promoter, and lack all or part of a phage gene encoding a protein required for the generation of infective phage particles, e.g., gI, gII,

gIII, gIV, gV, gVI, gVII, gVIII, gIX, gX, or gXI, or any combination thereof. For example, some M13 selection phage provided herein comprise a nucleic acid sequence encoding a protein to be evolved, e.g., under the control of an M13 promoter, and lack all or part of a gene encoding a protein required for the generation of infective phage particles, e.g., the gIII gene encoding the pIII protein. In some embodiments, an M13 selection phage comprises a nucleic acid sequence encoding a protein that interacts with the protein to be evolved (e.g., the TBR of a Bt toxin receptor).

[0065] The term “helper phage,” as used herein interchangeably with the terms “helper phagemid” and “helper plasmid,” refers to a nucleic acid construct comprising a phage gene required for the phage life cycle, or a plurality of such genes, but lacking a structural element required for genome packaging into a phage particle. For example, a helper phage may provide a wild-type phage genome lacking a phage origin of replication. In some embodiments, a helper phage is provided that comprises a gene required for the generation of phage particles, but lacks a gene required for the generation of infectious particles, for example, a full-length pIII gene. In some embodiments, the helper phage provides only some, but not all, genes required for the generation of phage particles. Helper phages are useful to allow modified phages that lack a gene required for the generation of phage particles to complete the phage life cycle in a host cell. Typically, a helper phage will comprise the genes required for the generation of phage particles that are lacking in the phage genome, thus complementing the phage genome. In the continuous evolution context, the helper phage typically complements the selection phage, but both lack a phage gene required for the production of infectious phage particles.

[0066] The term “replication product,” as used herein, refers to a nucleic acid that is the result of viral genome replication by a host cell. This includes any viral genomes synthesized by the host cell from a viral genome inserted into the host cell. The term includes non-mutated as well as mutated replication products.

Accessory Plasmids and Helper Constructs

[0067] The term “accessory plasmid,” as used herein, refers to a plasmid comprising a gene required for the generation of infectious viral particles under the control of a conditional promoter. In the context of continuous evolution described herein, the conditional promoter of the accessory plasmid is typically activated by a function of the gene of interest to be evolved. Accordingly, the accessory plasmid serves the function of conveying a competitive advantage to those viral vectors in a given population of viral vectors that carry a gene of interest able to activate the conditional promoter. Only viral vectors carrying an “activating” gene of interest will be able to induce expression of the gene required to generate infectious viral particles in the host cell, and, thus, allow for packaging and propagation of the viral genome in the flow of host cells. Vectors carrying non-activating versions of the gene of interest, on the other hand, will not induce expression of the gene required to generate infectious viral vectors, and, thus, will not be packaged into viral particles that can infect fresh host cells.

[0068] In some embodiments, the conditional promoter of the accessory plasmid is a promoter that promotes the transcriptional activity of which can be regulated over a wide range, for exam-

ple, over 2, 3, 4, 5, 6, 7, 8, 9, or 10 orders of magnitude by the activating function, for example, function of a protein encoded by the gene of interest). In some embodiments, the level of transcriptional activity of the conditional promoter depends directly on the desired function of the gene of interest. This allows for starting a continuous evolution process with a viral vector population comprising versions of the gene of interest that only show minimal activation of the conditional promoter. In the process of continuous evolution, any mutation in the gene of interest that increases activity of the conditional promoter directly translates into higher expression levels of the gene required for the generation of infectious viral particles, and, thus, into a competitive advantage over other viral vectors carrying minimally active or loss-of-function versions of the gene of interest.

[0069] The stringency of selective pressure imposed by the accessory plasmid in a continuous evolution procedure as provided herein can be modulated. In some embodiments, the use of low copy number accessory plasmids results in an elevated stringency of selection for versions of the gene of interest that activate the conditional promoter on the accessory plasmid, while the use of high copy number accessory plasmids results in a lower stringency of selection. The terms “high copy number plasmid” and “low copy number plasmid” are art-recognized and those of skill in the art will be able to ascertain whether a given plasmid is a high or low copy number plasmid. In some embodiments, a low copy number accessory plasmid is a plasmid exhibiting an average copy number of plasmid per host cell in a host cell population of about 5 to about 100. In some embodiments, a very low copy number accessory plasmid is a plasmid exhibiting an average copy number of plasmid per host cell in a host cell population of about 1 to about 10. In some embodiments, a very low copy number accessory plasmid is a single-copy per cell plasmid. In some embodiments, a high copy number accessory plasmid is a plasmid exhibiting an average copy number of plasmid per host cell in a host cell population of about 100 to about 5000. The copy number of an accessory plasmid will depend to a large part on the origin of replication employed. Those of skill in the art will be able to determine suitable origins of replication in order to achieve a desired copy number.

[0070] It should be understood that the function of the accessory plasmid, namely to provide a gene required for the generation of viral particles under the control of a conditional promoter the activity of which depends on a function of the gene of interest, can be conferred to a host cell in alternative ways. Such alternatives include, but are not limited to, permanent insertion of a gene construct comprising the conditional promoter and the respective gene into the genome of the host cell, or introducing it into the host cell using an different vector, for example, a phagemid, a cosmid, a phage, a virus, or an artificial chromosome. Additional ways to confer accessory plasmid function to host cells will be evident to those of skill in the art, and the invention is not limited in this respect.

Mutagens and Mutagenesis-Promoting Expression Constructs

[0071] The term “mutagen,” as used herein, refers to an agent that induces mutations or increases the rate of mutation in a given biological system, for example, a host cell, to a level above the naturally-occurring level of mutation in

that system. Some exemplary mutagens useful for continuous evolution procedures are provided elsewhere herein and other useful mutagens will be evident to those of skill in the art. Useful mutagens include, but are not limited to, ionizing radiation, ultraviolet radiation, base analogs, deaminating agents (e.g., nitrous acid), intercalating agents (e.g., ethidium bromide), alkylating agents (e.g., ethylnitrosourea), transposons, bromine, azide salts, psoralen, benzene, 3-Chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone (MX) (CAS no. 77439-76-0), O,O-dimethyl-S-(phthalimido-methyl)phosphorodithioate (phos-met) (CAS no. 732-11-6), formaldehyde (CAS no. 50-00-0), 2-(2-furyl)-3-(5-nitro-2-furyl)acrylamide (AF-2) (CAS no. 3688-53-7), glyoxal (CAS no. 107-22-2), 6-mercaptopurine (CAS no. 50-44-2), N-(trichloromethylthio)-4-cyclohexane-1,2-dicarboximide (captan) (CAS no. 133-06-2), 2-aminopurine (CAS no. 452-06-2), methyl methane sulfonate (MMS) (CAS No. 66-27-3), 4-nitroquinoline 1-oxide (4-NQO) (CAS No. 56-57-5), N4-Aminocytidine (CAS no. 57294-74-3), sodium azide (CAS no. 26628-22-8), N-ethyl-N-nitrosourea (ENU) (CAS no. 759-73-9), N-methyl-N-nitrosourea (MNU) (CAS no. 820-60-0), 5-azacytidine (CAS no. 320-67-2), cumene hydroperoxide (CHP) (CAS no. 80-15-9), ethyl methanesulfonate (EMS) (CAS no. 62-50-0), N-ethyl-N-nitro-N-nitrosoguanidine (ENNG) (CAS no. 4245-77-6), N-methyl-N-nitro-N-nitrosoguanidine (MNNG) (CAS no. 70-25-7), 5-diazouracil (CAS no. 2435-76-9) and t-butyl hydroperoxide (BHP) (CAS no. 75-91-2). Additional mutagens can be used in continuous evolution procedures as provided herein, and the invention is not limited in this respect.

[0072] Ideally, a mutagen is used at a concentration or level of exposure that induces a desired mutation rate in a given host cell or viral vector population, but is not significantly toxic to the host cells used within the average time frame a host cell is exposed to the mutagen or the time a host cell is present in the host cell flow before being replaced by a fresh host cell.

[0073] The term “mutagenesis plasmid,” as used herein, refers to a plasmid comprising a gene encoding a gene product that acts as a mutagen. In some embodiments, the gene encodes a DNA polymerase lacking a proofreading capability. In some embodiments, the gene is a gene involved in the bacterial SOS stress response, for example, a UmuC, UmuD', or RecA gene. In some embodiments, the gene is a GATC methylase gene, for example, a deoxyadenosine methylase (dam methylase) gene. In some embodiments, the gene is involved in binding of hemimethylated GATC sequences, for example a seqA gene. In some embodiments, the gene is involved with repression of mutagenic nucleobase export, for example emrR. In some embodiments, the gene is involved with inhibition of uracil DNA-glycosylase, for example a Uracil Glycosylase Inhibitor (ugi) gene. In some embodiments, the gene is involved with deamination of cytidine (e.g., a cytidine deaminase from *Petromyzon marinus*), for example, cytidine deaminase 1 (CDA1).

Host Cells

[0074] The term “host cell,” as used herein, refers to a cell that can host a viral vector useful for a continuous evolution process as provided herein. A cell can host a viral vector if it supports expression of genes of viral vector, replication of the viral genome, and/or the generation of viral particles.

One criterion to determine whether a cell is a suitable host cell for a given viral vector is to determine whether the cell can support the viral life cycle of a wild-type viral genome that the viral vector is derived from. For example, if the viral vector is a modified M13 phage genome, as provided in some embodiments described herein, then a suitable host cell would be any cell that can support the wild-type M13 phage life cycle. Suitable host cells for viral vectors useful in continuous evolution processes are well known to those of skill in the art, and the invention is not limited in this respect.

[0075] In some embodiments, modified viral vectors are used in continuous evolution processes as provided herein. In some embodiments, such modified viral vectors lack a gene required for the generation of infectious viral particles. In some such embodiments, a suitable host cell is a cell comprising the gene required for the generation of infectious viral particles, for example, under the control of a constitutive or a conditional promoter (e.g., in the form of an accessory plasmid, as described herein). In some embodiments, the viral vector used lacks a plurality of viral genes. In some such embodiments, a suitable host cell is a cell that comprises a helper construct providing the viral genes required for the generation of viral particles. A cell is not required to actually support the life cycle of a viral vector used in the methods provided herein. For example, a cell comprising a gene required for the generation of infectious viral particles under the control of a conditional promoter may not support the life cycle of a viral vector that does not comprise a gene of interest able to activate the promoter, but it is still a suitable host cell for such a viral vector. In some embodiments, the viral vector is a phage and the host cell is a bacterial cell. In some embodiments, the host cell is an *E. coli* cell. Suitable *E. coli* host strains will be apparent to those of skill in the art, and include, but are not limited to, New England Biolabs (NEB) Turbo, Top10F', DH12S, ER2738, ER2267, XL1-Blue MRF', and DH10B. These strain names are art recognized and the genotype of these strains has been well characterized. It should be understood that the above strains are exemplary only and that the invention is not limited in this respect.

[0076] The term “fresh,” as used herein interchangeably with the terms “non-infected” or “uninfected” in the context of host cells, refers to a host cell that has not been infected by a viral vector comprising a gene of interest as used in a continuous evolution process provided herein. A fresh host cell can, however, have been infected by a viral vector unrelated to the vector to be evolved or by a vector of the same or a similar type but not carrying the gene of interest. In some embodiments, the host cell is a prokaryotic cell, for example, a bacterial cell.

[0077] In some embodiments, the host cell is an *E. coli* cell. In some PACE embodiments, for example, in embodiments employing an M13 selection phage, the host cells are *E. coli* cells expressing the Fertility factor, also commonly referred to as the F factor, sex factor, or F-plasmid. The F-factor is a bacterial DNA sequence that allows a bacterium to produce a sex pilus necessary for conjugation and is essential for the infection of *E. coli* cells with certain phage, for example, with M13 phage. For example, in some embodiments, the host cells for M13-PACE are of the genotype F'proA⁺B⁺ Δ(lacIZY) zzf::Tn10(TetR)/endA1 recA1 galE15 galK16 nupG rpsL ΔlacIZYA araD139 Δ(ara, leu)7697 mcrA Δ(mrr-hsdRMS-mcrBC)

proBA::pir116 λ⁻. In some embodiments, the host cells for M13-PACE are of the genotype F'proA⁺B⁺ Δ(lacIZY) zzf::Tn10(TetR) lacIQ1PN25-tetR luxCDE/endA1 recA1 galE15 galK16 nupG rpsL(StrR) ΔlacIZYA araD139 Δ(ara, leu)7697 mcrA Δ(mrr-hsdRMS-mcrBC) proBA::pir116 araE201 ΔrpoZ Δflu ΔcsgABCDEF G ΔpgaC λ⁻, for example S1030 cells as described in Carlson, J. C., et al. Negative selection and stringency modulation in phage-assisted continuous evolution. *Nat. Chem. Biol.* 10, 216-222(2014). In some embodiments, the host cells for M13-PACE are of the genotype F' proA⁺B⁺ Δ(lacIZY) zzf::Tn10 lacIQ1 PN25-tetR luxCDE Psp(AR2) lacZ luxR Plux groESL / endA1 recA1 galE15 galK16 nupG rpsL ΔlacIZYA araD139 Δ(ara, leu)7697 mcrA Δ(mrr-hsdRMS-mcrBC) proBA::pir116 araE201 ΔrpoZ Δflu ΔcsgABCDEF G ΔpgaC λ⁻, for example S2060 cells as described in Hubbard, B. P. et al. Continuous directed evolution of DNA-binding proteins to improve TALEN specificity. *Nature Methods* 12, 939-942 (2015).

Pest Control

[0078] The term “pest,” as used herein, refers to a destructive insect or other animal that attacks crops, livestock, or other subjects (e.g., humans, domesticated animals, etc.). In the context of this disclosure, a pest is generally an insect. However, the skilled artisan recognizes that Bt toxin variants described by the disclosure may be useful against other types of pests, for example parasitic nematodes. The destruction caused by a pest or pests can be physical (e.g., damaging crops or causing physical harm to a subject), mental (e.g., continued irritation from pest activity), economic (e.g., loss of crops due to pest activity), or any combination of the foregoing.

[0079] The term “sensitive to treatment with Bt toxin,” refers to a pest that can effectively be controlled by treatment with Bt toxin (e.g., a wild-type Bt toxin).

[0080] The term “resistant to treatment with Bt toxin,” refers to a pest that is refractory to treatment with Bt toxin (e.g., a wild-type Bt toxin). Resistance to Bt toxin generally results from the reduction or absence of binding interactions between a Bt toxin and a cell surface receptor (e.g., a cadherin or cadherin-like receptor) that is present in the resistant subject (e.g., a Bt resistant pest).

DETAILED DESCRIPTION OF THE INVENTION

[0081] Some aspects of this disclosure provide variant Bt toxins and methods for producing the same. In some embodiments, the disclosure relates to the use of phage-assisted continuous evolution (PACE) to produce variant Bt toxins. In some embodiments, variant Bt toxins described by the disclosure bind targets (e.g., receptors) in resistant pests with higher affinity than the wild-type Bt toxin from which they are derived and are thus useful for controlling pests that are resistant to wild type Bt toxins. Some aspects of this disclosure provide methods for pest control using the Bt toxin variants provided herein.

Variant Bt Toxins

[0082] Some aspects of this disclosure provide variant Bt toxins that are derived from a wild-type Bt toxin and have at least one variation in the amino acid sequence of the protein as compared to the amino acid sequence present within a

cognate wild-type Bt toxin or at least one variation in the encoding nucleic acid sequence that results in a change in the amino acid sequence present within a cognate wild type Bt toxin. The variation in amino acid sequence generally results from a mutation, insertion, or deletion in a DNA coding sequence. Mutation of a DNA sequence can result in a nonsense mutation (e.g., a transcription termination codon (TAA, TAG, or TGA) that produces a truncated protein), a missense mutation (e.g., an insertion or deletion mutation that shifts the reading frame of the coding sequence), or a silent mutation (e.g., a change in the coding sequence that results in a codon that codes for the same amino acid normally present in the cognate protein, also referred to sometimes as a synonymous mutation). In some embodiments, mutation of a DNA sequence results in a non-synonymous (i.e., conservative, semi-conservative, or radical) amino acid substitution.

[0083] Wild-type Bt toxins are encoded by genes of the cry gene family, e.g., by the Cry1Ac gene. The amount or level of variation between a wild-type Bt toxin and a variant Bt toxin provided herein can be expressed as the percent identity of the nucleic acid sequences or amino acid sequences between the two genes or proteins. In some embodiments, the amount of variation is expressed as the percent identity at the amino acid sequence level. In some embodiments, a variant Bt toxin and a wild-type Bt toxin are from about 50% to about 99.9% identical, about 55% to about 95% identical, about 60% to about 90% identical, about 65% to about 85% identical, or about 70% to about 80% identical at the amino acid sequence level. In some embodiments, a variant Bt toxin comprises an amino acid sequence that is at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 99%, or at least 99.9% identical to the amino acid sequence of a wild-type Bt toxin.

[0084] In some embodiments, a variant Bt toxin is about 70%, about 71%, about 72%, about 73%, about 74%, about 75%, about 76%, about 77%, about 78%, about 79%, about 80%, about 81%, about 82%, about 83%, about 84%, about 85%, about 86%, about 87%, about 88%, about 89%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, or about 99.9% identical to a wild-type Bt toxin.

[0085] Some aspects of this disclosure relate to variant Cry1Ac proteins comprising an amino acid sequence that is about 70% identical to the amino acid sequence of wild-type Cry1Ac as provided in SEQ ID NO: 1, wherein the protein comprises at least one variation in the amino acid sequence of the protein provided in Table 1.

[0086] The amount or level of variation between a wild-type Bt toxin and a variant Bt toxin can also be expressed as the number of mutations present in the amino acid sequence encoding the variant Bt toxin relative to the amino acid sequence encoding the wild-type Bt toxin. In some embodiments, an amino acid sequence encoding a variant Bt toxin comprises between about 1 mutation and about 100 mutations, about 10 mutations and about 90 mutations, about 20 mutations and about 80 mutations, about 30 mutations and about 70 mutations, or about 40 and about 60 mutations relative to an amino acid sequence encoding a wild-type Bt toxin. In some embodiments, an amino acid sequence encoding a variant Bt toxin comprises more than 100 mutations relative to an amino acid sequence encoding a wild-type Bt toxin. Examples of mutations that occur in an

amino acid sequence encoding a variant Bt toxin are depicted in Table 1.

[0087] Accordingly, in some embodiments, a variant Bt toxin comprises at least 2, at least 3, at least 4, at least 5, at least 6, at least 7, at least 8, at least 9, at least 10, at least 11, at least 12, at least 13, at least 14, or at least 15 mutations provided in Table 1. Particular combinations of mutations present in an amino acid sequence encoding a variant Bt toxin can be referred to as the “genotype” of the variant Bt toxin. For example, a variant Bt toxin genotype may comprise the mutations G158G, S201Y, D487Y, T489A, S507C, and A681T, relative to a wild-type Bt toxin (e.g., SEQ ID NO: 1). Further examples of variant Bt toxin genotypes are shown in Table 2.

[0088] In some embodiments, the at least one mutation is selected from the group consisting of: C14W, C14R, F67S, R197G, G267G, T303N, M321K, E331G, A343E, Q352H, T360I, S362P, D383Y, S403C, N416D, E460K, N462S, D383Y, S403C, and S581L.

[0089] The location of mutations in an amino acid sequence encoding a variant Bt toxin are also contemplated by the disclosure. Generally, mutations may occur in any portion (e.g., N-terminal, interior, or C-terminal) of an amino acid sequence. Mutations may also occur in any functional domain (e.g., the pore-forming domain, the receptor-binding domain, or the sugar-binding domain). In some embodiments, at least one mutation is located in the receptor-binding domain of the Bt variant toxin, which correlates to the portion of the Bt variant toxin that interacts with the TBR of a target pest.

[0090] In some aspects, the disclosure relates to variant Bt toxins that bind to receptors in Bt toxin-resistant pests with higher affinity than the wild-type Bt toxin from which they are derived (e.g., Cry1Ac, represented by SEQ ID NO: 1). Generally, binding of a Bt toxin to a receptor is mediated by the interaction between the receptor binding domain (e.g., target binding region) of the Bt toxin and the cell surface receptor of the target cell. Thus, in some embodiments the disclosure provides a protein comprising a receptor binding domain, wherein the receptor binding domain comprises an amino acid sequence that is at least 70%, at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, or at least 99% identical to SEQ ID NO: 1, wherein the receptor binding domain comprises at least one mutation provided in Table 1, and wherein the variant Bt toxin binds a toxin binding region with higher affinity than a protein having the amino acid sequence of SEQ ID NO: 1.

[0091] This disclosure relates, in part, to the discovery that continuous evolution methods (e.g., PACE) are useful for producing variant Bt toxins that have altered receptor binding capabilities. In some embodiments, a variant Bt toxin binds to a toxin binding region of a cell surface receptor with higher affinity than the cognate Bt toxin. Several -binding cell surface receptors are known in the art. Examples of such cell surface receptors include, but are not limited to, cadherin-like proteins (CADR), glycosylphosphatidylinositol (GPI)-anchored aminopeptidase-N (APN), and GPI-anchored alkaline phosphatase (ALP). Cry1Ac does not bind to, or recognize these as a target receptor. A variant Bt toxin that binds with higher affinity can have an increase in binding strength ranging from about 2-fold to about 100-fold, about 5-fold to about 50-fold, or about 10-fold to about 40-fold, relative to the binding strength of the wild-type Bt toxin from which the variant Bt toxin was derived. Binding

strength can be measured or determined using any suitable method known in the art, for example by determining the dissociation constant (Kd) of an interaction.

Production of Variant Bt Toxins Using PACE

[0092] In some aspects, the disclosure relates to methods for producing variant Bt toxins using continuous evolution (e.g., PACE). The general concept of PACE technology has been described, for example in International PCT Application, PCT/US2009/056194, filed Sep. 8, 2009, published as WO 2010/028347 on Mar. 11, 2010; International PCT Application, PCT/US2011/066747, filed Dec. 22, 2011, published as WO 2012/088381 on Jun. 28, 2012; and U.S. Application, U.S.S.N. 13/922,812, filed Jun. 20, 2013, each of which is incorporated herein by reference. As described by the present disclosure, PACE allows for a gene of interest (e.g., a gene encoding a Bt toxin) in a viral vector to be evolved over multiple generations of viral life cycles in a flow of host cells to acquire a desired function or activity (e.g., increased binding affinity to a toxin binding region in a pest resistant to the wild type Bt toxin, e.g., in a situation in which the wild type Bt toxin has lost the ability to bind to and/or recognize the normal receptor in a particular target pest).

[0093] In some aspects, the disclosure provides a method for producing a Bt toxin variant, the method comprising: (a) contacting a population of bacterial host cells with a population of M13 phages comprising a first gene encoding a first fusion protein, and deficient in a full-length pIII gene, wherein (1) the fusion protein comprises a Bt toxin binding region (TBR) and a repressor element, (2) the phage allows for expression of the first fusion protein in the host cells, (3) the host cells are suitable host cells for M13 phage infection, replication, and packaging; and (4) the host cells comprise an expression construct comprising a second gene encoding the pIII protein and a third gene encoding a second fusion protein comprising a Bt toxin and an RNA polymerase, wherein expression of the pIII gene is dependent on interaction of the Bt toxin of the second fusion protein with the TBR of the first fusion protein; (b) incubating the population of host cells under conditions allowing for the mutation of the third gene, the production of infectious M13 phage, and the infection of host cells with M13 phage, wherein infected cells are removed from the population of host cells, and wherein the population of host cells is replenished with fresh host cells that are not infected by M13 phage; (c) isolating a mutated M13 phage replication product encoding an evolved second fusion protein from the population of host cells.

[0094] In some embodiments, the incubating of the host cells is for a time sufficient for at least 10, at least 20, at least 30, at least 40, at least 50, at least 100, at least 200, at least 300, at least 400, at least 500, at least 600, at least 700, at least 800, at least 900, at least 1000, at least 1250, at least 1500, at least 1750, at least 2000, at least 2500, at least 3000, at least 4000, at least 5000, at least 7500, at least 10000, or more consecutive viral life cycles. In certain embodiments, the viral vector is an M13 phage, and the length of a single viral life cycle is about 10-20 minutes.

[0095] In some embodiments, the cells are contacted and/or incubated in suspension culture. For example, in some embodiments, bacterial cells are incubated in suspension culture in liquid culture media. Suitable culture media for

bacterial suspension culture will be apparent to those of skill in the art, and the invention is not limited in this regard. See, for example, *Molecular Cloning: A Laboratory Manual*, 2nd Ed., ed. by Sambrook, Fritsch, and Maniatis (Cold Spring Harbor Laboratory Press: 1989); Elizabeth Kutter and Alexander Sulakvelidze: *Bacteriophages: Biology and Applications*. CRC Press; 1st edition (December 2004), ISBN: 0849313368; Martha R. J. Clokie and Andrew M. Kropinski: *Bacteriophages: Methods and Protocols, Volume 1: Isolation, Characterization, and Interactions (Methods in Molecular Biology)* Humana Press; 1st edition (December, 2008), ISBN: 1588296822; Martha R. J. Clokie and Andrew M. Kropinski: *Bacteriophages: Methods and Protocols, Volume 2: Molecular and Applied Aspects (Methods in Molecular Biology)* Humana Press; 1st edition (December 2008), ISBN: 1603275649; all of which are incorporated herein in their entirety by reference for disclosure of suitable culture media for bacterial host cell culture). Suspension culture typically requires the culture media to be agitated, either continuously or intermittently. This is achieved, in some embodiments, by agitating or stirring the vessel comprising the host cell population. In some embodiments, the outflow of host cells and the inflow of fresh host cells is sufficient to maintain the host cells in suspension. This in particular, if the flow rate of cells into and/or out of the culture vessel is high.

[0096] Generally, an accessory plasmid is required for selection of viral vectors, for example, the accessory plasmid comprising the gene required for the generation of infectious phage particles that is lacking from the phages being evolved. In some embodiments, an accessory plasmid comprises a first fusion protein comprising a Bt toxin TBR and a repressor element. In some embodiments, the host cells are generated by contacting an uninfected host cell with the relevant vectors, for example, the accessory plasmid and, optionally, a mutagenesis plasmid, and growing an amount of host cells sufficient for the replenishment of the host cell population in a continuous evolution experiment. Methods for the introduction of plasmids and other gene constructs into host cells are well known to those of skill in the art and the invention is not limited in this respect. For bacterial host cells, such methods include, but are not limited to electroporation and heat-shock of competent cells. In some embodiments, the accessory plasmid comprises a selection marker, for example, an antibiotic resistance marker, and the fresh host cells are grown in the presence of the respective antibiotic to ensure the presence of the plasmid in the host cells. Where multiple plasmids are present, different markers are typically used. Such selection markers and their use in cell culture are known to those of skill in the art, and the invention is not limited in this respect.

[0097] In some embodiments, the host cell population in a continuous evolution experiment is replenished with fresh host cells growing in a parallel, continuous culture. In some embodiments, the cell density of the host cells in the host cell population contacted with the viral vector and the density of the fresh host cell population is substantially the same.

[0098] In some embodiments, the host cell population is contacted with a mutagen. In some embodiments, the cell population contacted with the viral vector (e.g., the phage), is continuously exposed to the mutagen at a concentration that allows for an increased mutation rate of the gene of

interest, but is not significantly toxic for the host cells during their exposure to the mutagen while in the host cell population. In other embodiments, the host cell population is contacted with the mutagen intermittently, creating phases of increased mutagenesis, and accordingly, of increased viral vector diversification. For example, in some embodiments, the host cells are exposed to a concentration of mutagen sufficient to generate an increased rate of mutagenesis in the gene of interest for about 10%, about 20%, about 50%, or about 75% of the time.

[0099] In some embodiments, the host cells comprise a mutagenesis expression construct, for example, in the case of bacterial host cells, a mutagenesis plasmid. In some embodiments, the mutagenesis plasmid comprises a gene expression cassette encoding a mutagenesis-promoting gene product, for example, a proofreading-impaired DNA polymerase. In other embodiments, the mutagenesis plasmid, including a gene involved in the SOS stress response, (e.g., UmuC, UmuD', and/or RecA). In some embodiments, the mutagenesis-promoting gene is under the control of an inducible promoter. Suitable inducible promoters are well known to those of skill in the art and include, for example, arabinose-inducible promoters, tetracycline or doxycycline-inducible promoters, and tamoxifen-inducible promoters. In some embodiments, the host cell population is contacted with an inducer of the inducible promoter in an amount sufficient to effect an increased rate of mutagenesis. For example, in some embodiments, a bacterial host cell population is provided in which the host cells comprise a mutagenesis plasmid in which a dnaQ926, UmuC, UmuD', and RecA expression cassette is controlled by an arabinose-inducible promoter. In some such embodiments, the population of host cells is contacted with the inducer, for example, arabinose in an amount sufficient to induce an increased rate of mutation.

[0100] The use of an inducible mutagenesis plasmid allows one to generate a population of fresh, uninfected host cells in the absence of the inducer, thus avoiding an increased rate of mutation in the fresh host cells before they are introduced into the population of cells contacted with the viral vector. Once introduced into this population, however, these cells can then be induced to support an increased rate of mutation, which is particularly useful in some embodiments of continuous evolution. For example, in some embodiments, the host cell comprise a mutagenesis plasmid as described herein, comprising an arabinose-inducible promoter driving expression of dnaQ926, UmuC, UmuD', and RecA730 from a pBAD promoter (see, e.g., Khlebnikov A, Skaug T, Keasling JD. *Modulation of gene expression from the arabinose-inducible araBAD promoter*. J Ind Microbiol Biotechnol. 2002 Jul; 29(1):34-7; incorporated herein by reference for disclosure of a pBAD promoter). In some embodiments, the mutagenesis plasmid is an MP4 mutagenesis plasmid or an MP6 mutagenesis plasmid. The MP4 and MP6 mutagenesis plasmids are described, for example in U.S. Provisional Application Serial No. 62/149,378, filed on Apr. 17, 2015, the content of which is incorporated herein in its entirety. The MP4 mutagenesis plasmid comprises the following genes: dnaQ926, dam, seqA¹⁷. The MP6 mutagenesis plasmid comprises the following genes: dnaQ926, dam, seqA, emrR, Ugi, and CDA1²².

[0101] In some embodiments, the fresh host cells are not exposed to arabinose, which activates expression of the above identified genes and, thus, increases the rate of muta-

tions in the arabinose-exposed cells, until the host cells reach the lagoon in which the population of selection phage replicates. Accordingly, in some embodiments, the mutation rate in the host cells is normal until they become part of the host cell population in the lagoon, where they are exposed to the inducer (e.g., arabinose) and, thus, to increased mutagenesis. In some embodiments, a method of continuous evolution is provided that includes a phase of diversifying the population of viral vectors by mutagenesis, in which the cells are incubated under conditions suitable for mutagenesis of the viral vector in the absence of stringent selection for the mutated replication product of the viral vector encoding the evolved protein. This is particularly useful in embodiments in which a desired function to be evolved is not merely an increase in an already present function, for example, an increase in the transcriptional activation rate of a transcription factor, but the acquisition of a function not present in the gene of interest at the outset of the evolution procedure (for example, altered ligand binding specificity). A step of diversifying the pool of mutated versions of the gene of interest within the population of viral vectors, for example, of phage, allows for an increase in the chance to find a mutation that conveys the desired function.

[0102] In addition to altering the rate of mutagenesis, the selective stringency of host cells can be tuned. Such methods involving host cells of varying selective stringency allow for harnessing the power of continuous evolution methods as provided herein for the evolution of functions that are completely absent in the initial version of the gene of interest, for example, for the evolution of a transcription factor recognizing a foreign target sequence that a native transcription factor, used as the initial gene of interest, does not recognize at all. Or, for another example, the recognition of a desired target sequence by a DNA-binding protein, a recombinase, a nuclease, a zinc-finger protein, or an RNA-polymerase, that does not bind to or does not exhibit any activity directed towards the desired target sequence.

[0103] Other selection schemes for gene products having a desired activity are well known to those of skill in the art or will be apparent from the instant disclosure. Selection strategies that can be used in continuous evolution processes and methods as provided herein include, but are not limited to, selection strategies useful in two-hybrid screens. For example, the variant Bt toxin selection strategy described in more detail elsewhere herein is an example of a receptor recognition selection strategy.

[0104] In some embodiments, the stability of Bt toxin variants was enhanced by combinatorial reversion of mutations observed in PACE and subsequent stability screening of the resulting Bt toxin variants. For example, in some embodiments, the methods and strategies for evolving Bt toxin may include reverting back a single mutation or a combination of at least two, at least three, at least four, at least five, at least six, at least seven, at least eight, at least nine, or at least ten mutations observed in mutant Bt toxin clones obtained through PACE, and subsequently measuring the stability of the resulting Bt toxin variants (e.g., the stability in the presence of trypsin or other proteases and/or the thermal stability). In some embodiments, additional desirable parameters may also be assessed (e.g., affinity to a target receptor or toxicity to a target pest). In some embodiments, a strategy for improving PACE-derived Bt toxin variants may include multiple rounds of combinatorial reversion of mutations, e.g., wherein the first round includes the reversal of a single

mutation in a number of Bt toxin variants, and subsequent rounds include a systematic combination of reversions that are observed to have a beneficial effect (e.g., on stability or toxicity).

Vectors and Reagents

[0105] The invention provides viral vectors for methods related to the continuous evolution of Bt toxin. In some embodiments, phage vectors for phage-assisted continuous evolution are provided. In some embodiments, a selection phage is provided that comprises a phage genome deficient in at least one gene required for the generation of infectious phage particles and a gene of interest (e.g., a gene encoding a Bt toxin).

[0106] For example, in some embodiments, the selection phage comprises an M13 phage genome deficient in a gene required for the generation of infectious M13 phage particles, for example, a full-length gIII. In some embodiments, the selection phage comprises a phage genome providing all other phage functions required for the phage life cycle except the gene required for generation of infectious phage particles. In some such embodiments, an M13 selection phage is provided that comprises a gI, gII, gIV, gV, gVI, gVII, gVIII, gIX, gX, and gXI gene, but not a full-length gIII. In some embodiments, the selection phage comprises a 3'-fragment of gIII, but no full-length gIII. The 3'-end of gIII comprises a promoter and retaining this promoter activity is beneficial, in some embodiments, for an increased expression of gVI, which is immediately downstream of the gIII 3'-promoter, or a more balanced (wild-type phage-like) ratio of expression levels of the phage genes in the host cell, which, in turn, can lead to more efficient phage production. In some embodiments, the 3'-fragment of gIII gene comprises the 3'-gIII promoter sequence. In some embodiments, the 3'-fragment of gIII comprises the last 180 bp, the last 150 bp, the last 125 bp, the last 100 bp, the last 50 bp, or the last 25 bp of gIII. In some embodiments, the 3'-fragment of gIII comprises the last 180 bp of gIII.

[0107] M13 selection phage is provided that comprises a gene of interest in the phage genome, for example, inserted downstream of the gVIII 3'-terminator and upstream of the gIII-3'-promoter. In some embodiments, the gene of interest is a fusion protein comprising a toxin binding region of a Bt toxin receptor and a repressor element. In some embodiments, the repressor element is a lambda repressor element (lambda phage (λ) cI, or 434 cI), or a Zif268 repressor. In some embodiments, an M13 selection phage is provided that comprises a multiple cloning site for cloning a gene of interest into the phage genome, for example, a multiple cloning site (MCS) inserted downstream of the gVIII 3'-terminator and upstream of the gIII-3'-promoter.

[0108] Some aspects of this invention provide a vector system for continuous evolution procedures, comprising of a viral vector, for example, a selection phage, and a matching accessory plasmid. In some embodiments, a vector system for phage-based continuous directed evolution is provided that comprises (a) a selection phage comprising a gene encoding a protein that interacts with the protein to be evolved, wherein the phage genome is deficient in a gene required to generate infectious phage; and (b) an accessory plasmid comprising the gene required to generate infectious phage particle under the control of a conditional promoter, wherein the conditional promoter is activated by

the interaction of the protein expressed by the selection phage and the protein to be evolved.

[0109] In some embodiments, the selection phage is an M13 phage as described herein. In some embodiments, the selection phage comprises an M13 genome including all genes required for the generation of phage particles, for example, gI, gII, gIV, gV, gVI, gVII, gVIII, gIX, gX, and gXI gene, but not a full-length gIII gene. In some embodiments, the selection phage genome comprises an F1 or an M13 origin of replication. In some embodiments, the selection phage genome comprises a 3'-fragment of gIII gene. In some embodiments, the selection phage comprises a multiple cloning site upstream of the gIII 3'-promoter and downstream of the gVIII 3'-terminator.

[0110] In some embodiments, the selection phage does not comprise a full length gVI. GVI is similarly required for infection as gIII and, thus, can be used in a similar fashion for selection as described for gIII herein. However, it was found that continuous expression of pIII renders some host cells resistant to infection by M13. Accordingly, it is desirable that pIII is produced only after infection. This can be achieved by providing a gene encoding pIII under the control of an inducible promoter, for example, an arabinose-inducible promoter as described herein, and providing the inducer in the lagoon, where infection takes place, but not in the turbidostat, or otherwise before infection takes place. In some embodiments, multiple genes required for the generation of infectious phage are removed from the selection phage genome, for example, gIII and gVI, and provided by the host cell, for example, in an accessory plasmid as described herein.

[0111] The vector system may further comprise a helper phage, wherein the selection phage does not comprise all genes required for the generation of phage particles, and wherein the helper phage complements the genome of the selection phage, so that the helper phage genome and the selection phage genome together comprise at least one functional copy of all genes required for the generation of phage particles, but are deficient in at least one gene required for the generation of infectious phage particles.

[0112] In some embodiments, the accessory plasmid of the vector system comprises an expression cassette comprising the gene required for the generation of infectious phage under the control of a conditional promoter. In some embodiments, the accessory plasmid of the vector system comprises a gene encoding pIII under the control of a conditional promoter the activity of which is dependent on interaction of the protein expressed by the selection phage and the protein to be evolved. In some embodiments, the protein to be evolved is expressed by the host cells. In some embodiments, the protein to be evolved is a Bt toxin (e.g., Cry1Ac, SEQ ID NO:1). In some embodiments, the protein to be evolved is fused to a RNA polymerase that drives expression of the gene encoding pIII by interacting with the conditional promoter. In some embodiments, the RNA polymerase is RNA polymerase zeta (RpoZ) or RNA polymerase alpha (RpoA) and the conditional promoter is a lacZ promoter or a mutant lacZ promoter (e.g., P_{lacZ} -opt).

[0113] In some embodiments, the vector system further comprises a mutagenesis plasmid, for example, an arabinose-inducible mutagenesis plasmid as described herein (e.g., MP4 or MP6).

[0114] In some embodiments, the vector system further comprises a helper plasmid providing expression constructs

of any phage gene not comprised in the phage genome of the selection phage or in the accessory plasmid.

Pest Control

[0115] In some aspects, the disclosure relates to the surprising discovery that variant Bt toxins produced by continuous evolution are effective in killing pests that are normally refractory or resistant to treatment with the wild-type Bt toxin from which the variant Bt toxins are derived. (e.g., Cry1Ac, SEQ ID NO: 1).

[0116] Variant Bt toxins described by the disclosure may be effective against a wide variety of pests, for example insects. In some embodiments, the insects are selected from the group consisting of the insect Orders *Lepidoptera*, *Coleoptera*, *Hemiptera*, and *Diptera*.

[0117] Examples of *Lepidoptera* include *Zeuzera coffeae*, *Hyalarcta* spp., *Eumeta* spp., *Agrotis ipsilon*, *Pseudaletia unipuncta*, *Spodoptera frugiperda*, *Helicoverpa zea*, *Manduca sexta*, *Manduca quinquemaculata*, *Spodoptera exigua*, *Peridroma saucia*, *Ostrinia nubilalis*, *Colias eurytheme*, *Plathypena scabra*, *Pieris rapae*, *Plutella xylostella*, *Trichoplusia ni*, *Evergestos ro*, *Evergestos psa*, *Evergestos os*, and *Pthorimaea operculella*.

[0118] Examples of *Coleoptera* include *Agroites mancus*, *Limonijs agonus*, *white grub*, *Chaetocnema pulicaria*, *Carpophilus lugubris*, *Popilia japonica*, *Diabrotica barberi*, *Diabrotia undecimpunctata howardi*, *Diabrotica virgifera*, *Epitrix cucumeris*, *Epitrix fuscata*, *Systema blanda*, *Leptinotarsa decemlineata*, *Cerotoma trifurcata*, *Epilachna varivestis*, *Phyllotreta striolata*, *Phyllotreta cruciferae*, *Acalymma vittata*, *Metriorhiza bicolor*, *Systema blanda*, *Crioceris asparagi*, *Crioceris duodecimpunctata*, *Disonychia xanthomelas*, *Epitrix* spp., *Leptinotarsa decemlineata*, and *Epicauta* spp.

[0119] Examples of *Diptera* include *Delia platura*, *Zonosemata electa*, *Delia radicum*, *Delia antique*, *Liriomyza sativae*, *Pegomya hyoscyami*, *Anopheles* spp., *Aedes* spp., *Culex* spp., *Onchocerca volvulus*, *Phlebotomus* spp., *Lutzomyia* spp., *Chrysops* spp., *Tabanus* spp., *Glossina* spp., *Musca domestica*, and *Stomoxys* spp.

[0120] In some aspects, the disclosure provides methods of pest control, the method comprising providing to a pest a variant Bt toxin. Methods of pest control described herein may therefore be useful for controlling pests that are resistant to treatment with certain known and available wild-type Bt toxins.

[0121] Historically, Bt toxin has been used to control populations of pests that damage crops. For example Bt toxin can be topically applied to plants affected by pests as an insecticide. In other cases, plants, such as corn (*Zea mays*), cotton (*Gossypium* sp.), rice (*Oryza sativa* L.), alfalfa (*Medicago sativa*), potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), soybean (*Glycine max*), tobacco (*Nicotiana* sp.), and others can be genetically modified to express Bt toxin. Thus, in some embodiments, the disclosure provides cells and/or plants comprising a variant Bt toxin, e.g., in the form of a variant Bt toxin expressed from a recombinant nucleic acid encoding a variant Bt toxin provided herein. In some embodiments, the cell is a plant cell. Suitable methods of engineering plant cells and plants to express genes, including wild-type Bt genes, are well known to those of skill in the art, and such methods

can be used to produce plant cells and plants expressing the Bt toxin variants provided herein.

[0122] Transgenic plant which expresses a nucleic acid segment encoding a novel Bt toxin variant as described herein can be produced utilizing variations of methods well known in the art. In general, such methods comprise transforming a suitable host cell with a DNA segment which contains a promoter operatively linked to a coding region that encodes one or more of the Bt toxin variants. Such a coding region is generally operatively linked to a transcription-terminating region, whereby the promoter is capable of driving the transcription of the coding region in the cell, and hence providing the cell the ability to produce the encoded toxin in vivo. Vectors, plasmids, cosmids, and DNA segments for use in transforming such cells will generally comprise operons, genes, or gene-derived sequences, either native, or synthetically-derived, and particularly those encoding the disclosed Bt toxin variant proteins. These DNA constructs can further include structures such as promoters, enhancers, polylinkers, or other gene sequences which can have regulating activity upon the particular genes of interest. Without limitation, examples of plant transformation vectors include those derived from a Ti plasmid of *Agrobacterium tumefaciens*, as well as those disclosed, e.g., by Herrera-Estrella (Nature 303:209-213, 1983), Bevan (Nature 304:184-187, 1983), Klee (Bio/Technol. 3:637-642, 1985). Transgenic plants are desirable for increasing the insecticidal resistance of a monocotyledonous or dicotyledonous plant, by incorporating into such a plant a transgenic DNA segment encoding one or more Bt toxin variant proteins which are toxic to insects. In a related aspect, the present disclosure also encompasses a seed produced by the transformed plant, a progeny from such seed, and a seed produced by the progeny of the original transgenic plant, e.g., produced in accordance with the above process. Such progeny and seeds will have a Bt toxin variant protein-encoding transgene stably incorporated into their genome, and such progeny plants will inherit the traits afforded by the introduction of a stable transgene.

[0123] Examples of techniques for introducing DNA into plant tissue are disclosed in European Patent Application Publication No. 0 289 479, published Nov. 1, 1988, of Monsanto Company and by Perlak et al. in "Modification of the Coding Sequence Enhances Plant Expression of Insect Control Protein Genes," Proc. Natl. Acad. Sci. USA, 88, pp. 3324-3328 (1991). Examples of methods which can be modified for obtaining transgenic plants that express insect-active proteins include those describing, for example, Cry1A proteins (U.S. Pat. No. 5,880,275), Cry1B (U.S. Pat. Application Publication No. 2006/0112447), Cry1C (U.S. Pat. No. 6,033,874), Cry1A/F chimeras (U.S. Pat. Nos. 7,070,982; 6,962,705, and 6,713,063), and a Cry2Ab protein (U.S. Pat. No. 7,064,249), the entire contents of each of which are incorporated herein by reference.

[0124] Cells comprising variant Bt toxin can be isolated (e.g., cultured or stored in vitro), or can form part of a plant (e.g., a transgenic plant expressing a variant Bt toxin) or an entire plant, rendering the respective plant resistant to pests susceptible to the variant Bt toxin. Such pests may include, in some embodiments, pests that are resistant or refractory to wild-type Bt toxin.

[0125] The function and advantage of these and other embodiments of the present invention will be more fully understood from the Examples below. The following Exam-

ples are intended to illustrate the benefits of the present invention and to describe particular embodiments, but are not intended to exemplify the full scope of the invention. Accordingly, it will be understood that the Examples are not meant to limit the scope of the invention.

EXAMPLES

Materials and Methods

[0126] General methods. All PCR reactions were performed using PfuTurbo Cx Hotstart DNA polymerase (Agilent Technologies), VeraSeq ULtra DNA polymerase (Enzymatics) or Phusion U Hot Start DNA Polymerase (Life Technologies). Water was purified using a MilliQ water purification system (Millipore, Billerica MA). All plasmids and selection phages were constructed using USER cloning (New England Biolabs). Genes were synthesized as bacterial codon-optimized gBlocks Gene Fragments (Integrated DNA Technologies). All DNA cloning was carried out using NEB Turbo cells (New England Biolabs).

[0127] Electrocompetent strain preparation. Strain S1030 was used for all luciferase and plaque assays, as well as continuous evolution experiments. The glycerol stock of S1030 cells was used to seed a 2 mL overnight culture using 2xYT media supplemented with 10 µg/mL tetracycline (Sigma Aldrich), 50 µg/mL streptomycin (Sigma Aldrich), 10 µg/mL fluconazole (TCI America), and 10 µg/mL amphotericin B (TCI America) in a 37° C. shaker at 230 rpm. The saturated culture was diluted 1000-fold in 50 mL of the same supplemented media and grown under the same conditions until it reached mid log-phase (OD_{600} 0.5-0.8). Once the appropriate OD_{600} had been reached, the cells were pelleted in a 50 mL conical tube (VWR) for 5 mins at 10,000 rcf. The supernatant was immediately decanted and the interior of the tube was wiped with a few Kimwipes (Kimberly-Clark) to remove residual media and salts. The cells were resuspended in 25 mL of pre-chilled, sterile filtered 10% glycerol in MilliQ purified water using a pipette to quickly breakup the pellet. The cells were centrifuged and washed an additional three times. After the last centrifugation step, the interior of the tube was wiped with a few Kimwipes to remove residual glycerol solution. The pellet was resuspended in as little volume as possible, typically -150 µL, and split into 10 µL aliquots for storage. Cells were flash frozen using a liquid N₂ bath, then quickly transferred to -80° C. for extended storage. Electrocompetent S1030 cells produced by this method typically yielded 10⁷-10⁸ colonies/µg plasmid DNA.

[0128] General USER cloning. All plasmid and phage materials were constructed via USER cloning. Briefly, primers were designed to include a single internal deoxyuracil base ~15-20 bases from the 5' end of the primer, specifying this region as the USER junction. Criteria for design of the USER junction were: the junction should contain minimal secondary structure, have 45° C. < T_m < 70° C., and begin with a deoxyadenosine and end with a deoxythymine (to be replaced by deoxyuridine). The USER junction specifies the homology required for correct assembly. PfuTurbo Cx Hotstart DNA polymerase (Agilent Technologies), VeraSeq ULtra DNA polymerase (Enzymatics) or Phusion U Hot Start DNA Polymerase (Life Technologies) are able to use primers carrying deoxyuracil bases, whereas alternative

polymerases undergo a phenomenon known as PCR poisoning and do not extend the primer.

[0129] All PCR products were purified using MinElute PCR Purification Kit (Qiagen) to 10 µL final volume and quantified using a NanoDrop 1000 Spectrophotometer (Thermo Scientific). For assembly, PCR products carrying complementary USER junctions were mixed in an equimolar ratio (up to 1 pmol each) in a 10 µL reaction containing 15 units DpnI (NEB), 0.75 units USER (Uracil-Specific Excision Reagent) enzyme (Endonuclease VIII and Uracil-DNA Glycosylase, NEB), 50 mM Potassium Acetate, 20 mM Tris-acetate, 10 mM Magnesium Acetate, 100 µg/ml BSA at pH 7.9 (1x CutSmart Buffer, NEB). The reactions were incubated at 37° C. for 45 min, followed by heating to 80° C. and slow cooling to 22° C. (0.1° C./s). The hybridized constructs were directly used for heat-shock transformation of chemically competent NEB turbo *E. coli* cells according to the manufacturer's instructions. Transformants were selected on 1.8% agar-2xYT plates supplemented with the appropriate antibiotic(s).

[0130] For SP cloning, the hybridized constructs were purified using EconoSpin purification columns (Epoch Life Sciences), eluted using 25 µL 10% glycerol, and transformed into electrocompetent S1030 cells carrying the phage responsive AP pJC175e, which produces functional pIII in response to phage infection (this strain is henceforth referred to as S2208). Following recovery for 3-4 hours at 37° C. using unsupplemented 2xYT media, the culture was centrifuged and the supernatant was purified using a 0.22 µm PVDF Ultrafree centrifugal filter (Millipore). The supernatant was diluted in 100-fold increments and used in plaque assays using log-phase S2208 cells. Following overnight at 37° C., single plaques were picked into unsupplemented 2xYT media and grown for ~12 h in a 37° C. at 230 rpm. The supernatant was purified again to yield clonal phage stocks. In all cases, cloned plasmids and phages were prepared using the TempliPhi 500 Amplification Kit (GE Life Sciences) according to the manufacturer's protocol and verified by Sanger sequencing.

[0131] Plaque assays. S1030 cells transformed with the AP of interest were grown in 2xYT liquid media supplemented with the appropriate antibiotics to an OD_{600} of 0.6-0.9. The phage supernatant was diluted in three, 100-fold increments to yield 4 total samples (undiluted, 10⁻², 10⁻⁴, 10⁻⁶) to be used for infections. For each sample, 150 µL of cells were added to 10 µL of phage that had been filtered using a 0.22 µm PVDF Ultrafree centrifugal filter (Millipore). Within 1-2 min of infection, 1 mL of warm (~55° C.) top agar (7 g/L bacteriological agar in 2xYT) was added to the phage/cell mixture, mixed by pipetting up and down once, and plated onto quartered plates that had been previously poured with 2 mL of bottom agar (18 g/L bacteriological agar in 2xYT) in each quadrant. The plates were then grown overnight at 37° C. before plaques were observed.

[0132] Phage-Assisted Continuous Evolution (PACE). Host cell cultures, lagoons, media, and the PACE apparatus were prepared. The likelihood of recombinant, wild type selection phage ("SP") occurrence in an SP stock increases with extended standing culture growth of SP. To limit the enrichment of these SP during PACE, all SPs are repurified prior to any continuous evolution experiments. Briefly, SPs were plaqued using S2208 cells to yield single plaques. A single plaque was picked into 2 mL 2xYT supplemented

with the appropriate antibiotics and grown until the culture reached mid log-phase (OD_{600} 0.5-0.8). The culture was centrifuged using a tabletop centrifuge for 2 min at 10,000 rcf, followed by supernatant filtration using a 0.22 μ m PVDF Ultrafree centrifugal filter (Millipore). This short growth time routinely yields titers of 10^6 - 10^8 pfu/mL.

[0133] To prepare the PACE strain, the accessory plasmid (AP) and mutagenesis plasmid (MP) were co-transformed into electrocompetent S1030 cells and recovered using Davis rich media (DRM) to ensure MP repression. Transformations were plated on 1.8% agar-2xYT containing 50 μ g/mL carbenicillin, 40 μ g/mL chloramphenicol, 10 μ g/mL fluconazole, 10 μ g/mL amphotericin B, 100 mM glucose (United States Biological) and grown for 12-18 h in a 37° C. incubator. Following overnight growth, 4 single colonies were picked and resuspended in DRM, then serially diluted and plated on 1.8% agar-2xYT containing 50 μ g/mL carbenicillin, 40 μ g/mL chloramphenicol, 10 μ g/mL fluconazole, 10 μ g/mL amphotericin B, and either 100 mM glucose or 100 mM arabinose (Gold Biotechnology) and grown for 12-18 h in a 37° C. incubator. Concomitant with this plating step, the dilution series was used to inoculate liquid cultures in DRM supplemented with 50 μ g/mL carbenicillin, 40 μ g/mL chloramphenicol, 10 μ g/mL tetracycline, 50 μ g/mL streptomycin, 10 μ g/mL fluconazole, 10 μ g/mL amphotericin B and grown for 12-18 h in a 37° C. shaker at 230 rpm. Following confirmation of arabinose sensitivity using the plate assay, cultures of the serially diluted colonies still in log-phase growth were used to seed a 25 mL starter culture for the PACE chemostat.

[0134] Once the starter culture had reached log-phase density, the 25 mL culture was added directly to 175 mL of fresh DRM in the chemostat. The chemostat culture was maintained at 200 mL and grown at a dilution rate of 1.5-1.6 vol/hr. Lagoons flowing from the chemostats were maintained at 40 mL, and diluted as described for each experiment. Lagoons were supplemented with 25 mM arabinose to induce the MP for 8-16 h prior to infection with packaged SP. Samples were taken at the indicated time points, centrifuged at 10,000 rcf for 2 min, then sterile filtered with a 0.2 μ m filter and stored overnight at 4° C. Phage aliquots were titered on S2208 (total phage) and S1030 (wild type or recombinant phage) for all time points.

[0135] Mutagenesis during PACE. The basal mutation rate of replicating filamentous phage (7.2×10^{-7} substitutions/bp/generation) is sufficient to generate all possible single but not double mutants of a given gene in a 40 mL lagoon following one generation of phage replication. For the 2,139 bp rpoZ-cry1ac target, a basal mutation rate of 7.2×10^{-7} substitutions/bp/generation applied to 2×10^{10} copies of the gene (a single generation) in a 40 mL lagoon yields $\sim 3.1 \times 10^7$ base substitutions, easily enough to cover all 6,417 single point mutants but not all double mutants. Arabinose induction of MP6 can increase the mutation rate to 7.2×10^{-3} substitutions/bp/generation, yielding $\sim 3.1 \times 10^{11}$ substitutions spread over 2×10^{10} copies of the gene after a single generation. This elevated mutation rate is sufficient to cover all possible single (6.4×10^3), double (4.1×10^7) and triple (2.6×10^{11}) mutants after a single phage generation.

[0136] Luciferase assays. Expression plasmids (EPs) were co-transformed with an accessory plasmid ("AP") of interest into electrocompetent S1030 cells and plated onto 1.8% agar-2xYT plates with 50 μ g/mL carbenicillin and 100 μ g/mL spectinomycin. After overnight growth at 37° C., single

colonies were each picked into 2 mL DRM supplemented with 50 μ g/mL carbenicillin, 100 μ g/mL spectinomycin, 10 μ g/mL tetracycline, 50 μ g/mL streptomycin, 10 μ g/mL fluconazole, 10 μ g/mL amphotericin B and grown for 12-18 h in a 37° C. shaker at 230 rpm. Following overnight growth, cultures were diluted 1000-fold in a 96-well deep well plate containing 500 μ L DRM with 50 μ g/mL carbenicillin, 100 μ g/mL spectinomycin and the indicated arabinose concentration to induce rpoZ-cry1Ac expression from the EP. After growth with shaking at 37° C. for 4-5 hours, 150 μ L of each culture was transferred to a 96-well black wall, clear bottom plate (Costar), and the OD_{600} and luminescence for each well was measured on an Infinite M1000 Pro microplate reader (Tecan).

[0137] High-throughput sequencing and oligotype analysis. Raw reads are deposited in the NCBI Sequence Read Archive with accession number PRJNA293870, and all custom scripts used in analysis are available at github.com/MonsantoCo/BadranEtAl2015. Illumina reads obtained from each time point were mapped to the SP055-rpoZ-cMyc-Cry1Ac1-d123 reference sequence using bowtie v2.1.0, and the resulting SAM files were combined into a single BAM file using samtools v0.1.19. This BAM file was used as input to freebayes v0.9.21-12-28 g92eb53a to call SNPs, using the command "freebayes —use-best-n-alleles 1 —pooled-continuous —use-reference-allele —theta 500000000 —min-alternate-fraction 0.01 —ploidy 1 —region SP055-rpoZ-cMyc-Cry1Ac1-d123:2833-4971." The analysis is encapsulated in the custom script "ill.callsnps.sh." PacBio polymerase reads were demultiplexed with RS_Resequencing_Barcode.1 workflow provided by PacBio. Polymerase reads with quality score lower than 0.80 (defined by the PacBio scoring algorithm) or shorter than 50bp were filtered. High quality reads were processed into subreads after sequencing primers and adaptors were removed. Circular consensus reads (or reads-of-inserts) were obtained by calling consensus of subreads generated from the same polymerase reads. These circular consensus reads were mapped to the SP055-rpoZ-cMyc-Cry1Ac1-d123 reference sequence using BLASR v1.3.1.142244, and the alignment was exported as an aligned FASTA sequence using the custom script "SAM-toAFA.py." The aligned FASTA was used as input to the oligotyping platform, manually specifying entropy components as the positions at which the Illumina data defined informative SNPs. Only oligotypes that occur at > 1% in at least one sample were retained. This methodology resulted in informative changes at 25 of the 27 specified components. Oligotypes with gaps at the specified components, likely due to indels in the PacBio sequencing or alignment, were reassigned to other oligotypes with nucleotides in those positions only when it could be done unambiguously, and discarded otherwise, resulting in a total fraction abundance < 1 in FIG. 19. The resulting oligotype percent abundance matrix was read into R and analyzed using the custom script "PedigreeAndMullerPlot.R." The pedigree was refined manually, assuming that single mutant derivatives of previous oligotypes are due to de novo mutation, while double, triple, or greater mutations that can be explained by recombination of previously observed oligotypes was due to recombination, since the latter are highly unlikely to arise by multiple point mutation after the start of the PACE experiment.

[0138] High-throughput primary Bt toxin preparation and analysis. Wild-type Cry1Ac was cloned into the Bt expression vector pMON262346 using BspQ1 endonuclease restriction sites. Consensus PACE-evolved Cry1Ac variants were synthesized (Gen9) and cloned into the Bt expression vector pMON262346 using Hot Fusion. Reversion mutants of consensus Cry1Ac PACE variants were generated via PCR with Phusion High-Fidelity DNA polymerase (New England Biolabs) and mutant primers followed by Hot Fusion into the Bt expression vector pMON262346. The resulting plasmids were transformed into the protease-deficient Bt strain EG1065044 703 for protein expression. Cells were grown from single colonies in 96-well plates (Thermo Scientific, AB-0932) overnight in 400 μ L Brain Heart Infusion Glycerol (BHIG) media (VWR) supplemented with 5 μ g/mL chloramphenicol. Overnight cultures were used to prepare glycerol stocks (15% glycerol final concentration) and stored at -80° C. for future protein expression. Following overnight growth, 10 μ L of each culture was used to inoculate 1 mL of complete C2 medium containing 5 μ g/mL chloramphenicol in 96-well plates. The plates were incubated at 26° C. with vigorous shaking at 550 rpm in a Multitron shaking incubator (Infors HT) for 72 hr. The cells were harvested by centrifugation at 3,200 G for 15 min at 4° C. The supernatant was decanted and a single 3.5 mm glass bead was added to each well of the plate. The pellet was then resuspended in 1 mL of TX wash buffer composed of 10 mM Tris-HCl, pH 7.5, 0.005% Triton X-100 supplemented with 25 units/mL Benzonase® (EMD Millipore), and 2 mM $MgCl_2$, incubated at room temperature for 30-60 min (with vigorous vortexing every 10 min), then centrifuged at 3,200 G for 15 min at 4° C. The resulting pellet was resuspended and centrifuged under identical conditions two additional times. The washed spore/crystal pellet from each 1-mL culture was solubilized in the 96-well plate using 300 μ L of solubilization buffer composed of 50 mM CAPS, pH 11, and 10 mM DTT, then incubated while shaking at room temperature for 1 h. The insoluble debris was pelleted by centrifugation at 3,200 G for 15 min at 4° C., and 200 μ L of the supernatant were transferred to a sterile U-bottom 96-well plate. To each well, 10 μ L of 0.2 mg/mL trypsin in 1 M Tris-HCl, pH 7.5 was added. The mixture was incubated at 37° C. for 2 h while shaking at 150 rpm, followed by quenching using 2 μ L 0.1 M PMSF. The solution was filtered using a Millipore multiscreen plate with a 0.22 μ m membrane. Protein stability was assessed by SDS-PAGE and quantified using spot densitometry. Proteins purified using this protocol were tested in downstream insect cell assays.

[0139] Secondary Bt toxin purification and analysis. Bt glycerol stocks described above were used for large-scale protein expression and purification. A 2-mL starter culture of BHIG medium supplemented with 5 μ g/mL chloramphenicol was inoculated from the glycerol stocks and grown overnight at 280 rpm in a 28° C. shaker. The following day, the saturated culture was transferred into 500 mL complete C2 medium containing 5 μ g/mL chloramphenicol in a 2 L baffled flask and grown for an additional 72 h at 26° C. while shaking at 280 rpm. Sporulation and crystal formation in the culture was verified by optical microscopy of a 2- μ L aliquot of the saturated Bt culture. Upon confirmation of crystals, the partially lysed sporulated cells were harvested by centrifugation at 10,000 G for 12 min at 4° C. The pellet was then resuspended in 100 mL TX wash buffer composed

of 10 mM Tris-HCl, pH 7.5, and 0.005% Triton X-100 supplemented with 0.1 mM PMSF, 25 units/mL Benzonase® (Sigma-Aldrich), and 2 mM $MgCl_2$, incubated at room temperature for 30-60 min (with vigorous vortexing every 10 min), then centrifuged at 3,200 G for 15 min at 4° C. The resulting pellet was resuspended and centrifuged under identical conditions two additional times. The washed spore/crystal pellet was solubilized in 120 mL 50 mM CAPS, pH 11, 10 mM DTT at room temperature for 1 h while shaking at 130 rpm. The solubilized protein was separated from the insoluble debris by centrifugation at 35,000 G for 20 min at 4° C.

[0140] The supernatant was transferred to a fresh flask, and then supplemented with 10 mL 0.2 mg/mL Trypsin in 1 M Tris-HCl at pH 7.5. The mixture was incubated at 30° C. for 2-6 h with shaking at 150 rpm and trypsinization was monitored by SDS-PAGE. Once the trypsin digestion reaction was complete, the mixture was centrifuged at 3,200 G for 15 min at 4° C. The clear supernatant was removed and mixed with PMSF to 1 mM final concentration. The sample was loaded on a 5-10 mL Q-Sepharose (GE Healthcare) anion exchange column at a flow-rate of 4 mL/min and the trypsin resistant core of the toxin was eluted in 25 mM sodium carbonate, pH 9 supplemented with 200- 400 mM NaCl. Fractions containing the toxin tryptic cores were pooled, concentrated (Millipore Amicon Ultra-15 centrifugal filter Units, Fisher) and 758 loaded on a Hiload Superdex 200 gel filtration column using an ÄKTA chromatography system (GE Healthcare, United Kingdom). The column was pre-equilibrated and run with 25 mM sodium carbonate at pH 10.5 supplemented with 1 mM β -mercaptoethanol. Only the monomer peak of the toxin fractions was collected in each case and concentrated to 1-3 mg/mL. The final protein concentration was quantified by spot densitometry. The quality of the trypsinized toxin was assessed using the peptide mass fingerprinting (PMF) method that was based on in-gel digestion of proteins by trypsin and mass spectrometry (MS) analysis of the resulted peptides.

[0141] T. ni receptor fragment expression and purification. Custom expression vectors pMON251427 and IS0008 (same as pMON251427 but with wild-type TnCAD) were used to express TnTBR3 and TnCAD fragments in *Escherichia coli*. Both vectors contain an N-terminal MBP-TVMV protease cleavage site tag and a C-terminal 6x histidine tag flanking the receptor fragment of interest, with the ORF driven by the T7 promoter. Expression vectors were transformed into commercial BL21 (λ DE3) competent cells (Life Technologies) that had been previously transformed with TVMV protease expression vector (pMON101695; encodes constitutive TVMV protease from a pACYC184 (New England Biolabs) backbone). A single colony was inoculated in 2 mL of LB media supplemented with 50 μ g/mL kanamycin and 25 μ g/mL chloramphenicol, and grown at 37° C. for 4 h to generate a starter culture, which was used to prepare glycerol stocks and stored at -80° C. for the future protein expression. A second starter culture was inoculated using the BL21 (λ DE3) strain glycerol stocks in 2 mL of LB media supplemented with 50 μ g/mL kanamycin and 25 μ g/mL chloramphenicol and grown in a 25° C. shaker (280 rpm) for 15 h. The culture was transferred into 500 mL of Terrific Broth medium (24 g/L yeast extract, 12 g/L tryptone, and 5 g/L glucose) supplemented with 50 μ g/mL kanamycin and 25 μ g/mL chloramphenicol, and

grown at 37° C. for 4 h at 280 rpm, then transferred to 15° C. and grown for an additional 48 h after supplementation with IPTG to a final concentration of 0.1 mM. The cells were harvested by centrifugation at 10,000 G for 787 12 min at 4° C.

[0142] The bacterial cell pellet was resuspended in affinity buffer A (25 mM Tris-HCl at pH 8.0, 0.5 M NaCl, 15 mM imidazole, and 0.2 mM CaCl₂) containing 125 units/mL of Benzonase (EMD Millipore), 10,000 units/mL of Chicken egg white lysozyme (Sigma Aldrich) and 1x BugBuster (Novagen). The cell slurry was incubated at room temperature for 15 min, followed by sonication using Cell Disruptor W-0375 (Heat Systems-Ultrasonics) at 45% Duty Cycle (output No.5) for 30 seconds with 60 second rests for a total of three cycles. The cell lysate was centrifuged at 35,000 G for 20 min at 4° C. The supernatant was loaded onto a 5-mL Ni-NTA column that had been pre-equilibrated using affinity buffer A. After extensive washing with affinity buffer A, the receptor fragment was eluted with the affinity buffer B (25 mM Tris-HCl at pH 8.0, 0.1 M NaCl, 250 mM imidazole, 0.2 mM CaCl₂). Fractions containing the receptor fragment were pooled, concentrated and loaded on a Hiload Superdex 200 gel filtration column using an ÄKTA chromatography system (GE Healthcare, United Kingdom). The column was pre-equilibrated and run with 25 mM Tris-HCl at pH 8.0, 0.1 M NaCl, 0.2 mM CaCl₂. Dimer and monomer peaks of the T. ni TBR3 and CAD fractions were collected separately and concentrated to 1-2 mg/mL. Only TnTBR3 and TnCAD monomers were used for Cry1Ac1 binding studies.

[0143] Fluorescence thermal shift (FTS) assays. All assays were performed using a BioRad CFX96 real-time PCR thermal cycler, enabling thermal manipulations and dye fluorescence detection. The fluorescence sensitive dye SYPRO orange (Life Technologies, S6650) was used at a 5x concentration in all assays. The temperature was increased by 0.5° C. each cycle over a temperature range of 25-90° C. Assay reactions were performed in 96-well white PCR plates (Bio-Rad, No. HSP9631), and heat-sealed (Thermo Scientific, No. ALPS3000) to reduce volume loss through evaporation. The data was analyzed using the CFX manager software.

[0144] Protein-protein interaction affinity measurement. The OctetQk (ForteBio) and the Dip and Read™ Ni-NTA (NTA) biosensors were used to measure the affinity of Cry1Ac and its variants to immobilized 6xHis-TnCAD or TnTBR3 receptor fragments in 25 mM Tris-HCl at pH 8.5, 0.1 M NaCl, 0.1 mg/ml BSA, 0.05% Tween 20 according to the manufacturer's instructions. Octet Data Acquisition 7.1.0.100 software was used for data acquisition, and ForteBio Data Analysis 7 software was used for data analysis. At least four readings at different Cry1Ac1 concentrations (2-100 nM) were used for each receptor fragment-Bt toxin interaction and a global fit was used to calculate binding affinities.

[0145] Insect-based cell assays. Sf9 cells (Life Technologies) were plated in Sf-900™ III SFM (Life Technologies) at a density of 50,000 cells/well in a 96-well optical bottom black plate (Nunc, Thermo Scientific). The cells were incubated at 27° C. overnight to allow for adherence to the plate. Following overnight incubation, the medium was aspirated from the cells and 100 µL of p3 or p4 generation (third or fourth generation of baculovirus amplification in Sf9 cells

following initial transfection with plasmid) recombinant baculovirus encoding each receptor diluted in SFM was added to each well. The plates were kept in a humidified environment to prevent evaporation and incubated at 27° C. for 48 h. Receptor expression was confirmed by western blotting. Toxins were diluted to the same protein concentration in 25 mM sodium carbonate at pH 11, supplemented with 1 mM β-mercaptoethanol, followed by an additional 10-fold dilution in unsupplemented Grace's Media with 2 µM SYTOX Green Nucleic Acid Stain (Life Technologies, S7020). The media was removed from the wells without disturbing the attached cells, and the diluted toxins or buffer controls were added to respective wells. The fluorescence was measured on a CLARIOstar microplate reader (BMG Labtech) after incubation for 4 h. The fluorescence intensity of control cells expressing β-glucuronidase (GUS) was subtracted from wells expressing the variable receptor fragments with or without toxins. Replicates were averaged and signal was plotted for each toxin condition.

[0146] Primary insect diet bioassays. Insect diet bioassays using the evolved consensus Cry1Ac variants were performed as previously described. Briefly, 200 mL of artificial diet in 96-well plates were overlaid with 20 mL aliquots of toxin Bt spore/crystal or Bt crystal suspension, dried, after which wells were infested with neonate insect eggs suspended in 0.2% agar, dried again, sealed with Mylar sheets, and incubated at 20° C., 60% RH, in complete darkness for 5 days. The plates were scored on day 5 for larval mortality and growth stunting. Each assay was carried out in three independent biological replicates with eight insects per replicate.

[0147] Secondary insect diet surface overlay bioassays. An inbred Bt-susceptible laboratory strain of *T. ni*, (designated the Cornell strain), and a Cry1Ac-resistant strain nearly isogenic to the Cornell strain, GLEN-Cry1Ac-BCS, were maintained on a wheat germ-based artificial diet at 27° C. with 50% humidity and a photoperiod of 16 h light and 8 h dark. Diet surface overlay bioassays were conducted to determine the insecticidal activity of the toxins in the susceptible and Cry1Ac-resistant *T. ni*, as previously described. Briefly, 200 µL of toxin solution was spread on the surface of 5 mL of artificial diet in 30-mL plastic rearing cups (diet surface area was ~7 cm²), and 10 neonatal larvae were placed into each rearing cup after the toxin solution had dried. For each bioassay, 7-8 concentrations of the toxin were used and each treatment included five replicates (50 larvae total per concentration). Larval growth inhibition (neonates that did not reach 2nd instar after 4 days) and mortality were recorded after 4 days of feeding. The observed larval growth inhibition and mortality were corrected using Abbott's formula. Both IC₅₀ and LC₅₀ values and their 95% confidence intervals were calculated by probit analysis using the computer program POLO (LeOra Software, 1997).

Results

Development of a Sensitive PPI Detection Platform

[0148] N-hybrid methods enable the detection of native protein-protein interactions. Described here is an n-hybrid system that can rapidly detect protein-protein interactions in vivo.

[0149] A bacterial 2-hybrid system (B2H) that robustly reports on protein-protein interactions (“PPIs”) in vivo that rely on a DNA-binding domain (typically phage repressor) covalently fused to the “bait” protein, which serves as one of the interacting domains was designed to be compatible with the Phage-Assisted Continuous Evolution (PACE) platform. The partner interacting domain (“prey”) is fused to an activation domain, one that binds to the *E. coli* RNA polymerase. On-target interactions between the bait and prey domains result in localization of the RNA polymerase upstream of a reporter gene, typically the bacterial β -galactosidase. PACE has been previously shown to enable the rapid directed evolution of a number of protein classes, requiring minimal researcher intervention and yielding variants with selection-specified properties.

[0150] Initial surveying of known mechanisms of transcriptional activation in *E. coli* yielded three proteins: the *E. coli* RNA polymerase alpha (RpoA) and omega (RpoZ), and the T4 phage anti-sigma factor AsiA. AsiA and RpoA yield moderate levels of transcriptional activation, but AsiA is toxic to *E. coli* and requires genomic modifications to native $\sigma 70$ subunit. RpoZ outperformed both alternative transcriptional activation mechanisms, enabling an average transcriptional activation of 17-fold. Using RpoZ, additional DNA-binding domains: murine zinc finger Zif268 and 434 phage cI repressor were assessed. Both λ and 434 cI outperformed Zif268, likely a consequence of their dimeric nature as compared to monomeric Zif268. Furthermore, repressor tetramerization or the use of monomeric repressor variants enabled modulation of transcriptional activation levels, consistent with changes in bait abundance.

[0151] From these observations, the 434 cI repressor and the omega subunit were selected for further optimizations. The degree of transcriptional activation was low (7-fold for RpoA and 17-fold for RpoZ) using the wild type P_{lacZ} promoter. Directed evolution precedent emphasizes the strong relationship between selection dynamic range and the ability to differentiate between variants of similar activities. To construct a system that would be optimized to select for high affinity interactions, the system was further modified such that the highest affinity interactions result in the greatest degree of transcriptional activation, while increasing the dynamic range to enable the detection of weaker interactions. A number of mutated P_{lacZ} -derived promoters were surveyed using both RpoA and RpoZ to increase the degree of transcriptional activation. Mutated promoters tested with RpoA resulted in moderate changes to the degree of transcriptional activation. Conversely, the majority of surveyed mutations to the P_{lacZ} promoter using RpoZ resulted in a greater distribution of transcriptional activation. Among the tested promoters, one variant enhanced the transcriptional activation from 17-fold to 200-fold using the RpoZ-HA4/434cI-SH2 pair, while moderately reducing the background transcription as compared to the wild type promoter. This sensitized promoter ($P_{lacZ-opt}$) was used for all further analysis and evolution experiments.

[0152] Using the described platform, the degree of transcriptional activation can be modulated by manipulations of the RBS (ribosome activating site) driving the reporter gene, DNA-binding domain abundance, operator distance from the $P_{lacZ-opt}$ promoter, and DNA-binding domain-bait linker length. Cumulatively, these results describe a highly

sensitized bacterial 2-hybrid system can potently on on-target interactions and can be easily tuned by the investigator.

PPI-PACE Rapidly Evolves Monobody-Antigen Interactions

[0153] The previously evolved monobody HA4 binds to the SH2 domain of ABL1 kinase with high affinity (~ 7 nM). Prior structural elucidation of the interacting pair highlighted a number of binding hotspots necessary for high affinity binding. Among those, HA4 Y87 interacts with the SH2 domain using a phosphate ion at the interface near the phosphotyrosine-binding pocket, potentially mimicking the native interaction. The mutation Y87A in HA4 was found to ablate binding to the SH2 domain, confirming the amino acid sequence variations’ functional significance at the interaction interface. When Y87A was introduced into HA4 using the highly sensitized bacterial 2-hybrid system described above, the degree of transcriptional activation was reduced to negligible levels, confirming the ability of the system to report on functional interactions in vivo. The use of this system in PACE was investigated next. An accessory plasmid (AP) was designed which carries two cassettes: (1) the geneIII-luxAB cassette under the control of $P_{lacZ-opt}$ with an upstream 434 operator (OR1), and (2) a low-level constitutive expression cassette encoding the 434cI-SH2. Similarly, a selection phage (SP) encoding the rpoZ-HA4 fusion gene was generated. Importantly, SP encoding the nonmutated HA4 enabled the development of robust, activity-dependent plaques on S2060 cells carrying the cognate AP, whereas SP encoding the HA4 Y87A mutant did not.

[0154] To demonstrate the capability of PPI-PACE in evolving novel protein-protein interactions, the nonfunctional HA4 Y87A mutant was evolved back to the functional HA4 parent monobody. This constitutes an extremely difficult evolution, as successful reversion to the wild type amino acid at this position requires three adjacent mutations (codon at position 87: alanine/GCG to tyrosine/TAT or TAC). Using PACE to enable genetic drift, the HA4_{Y87A} SP was propagated for 66 hours in the absence of selection pressure but under high mutagenesis, after which point the selection pressure was engaged and compared to the absence of genetic drift. In the cases where neither drift nor mutagenesis were engaged or where only mutagenesis was engaged, the phage quickly washed out under constant dilution conditions. However, if a prior drift schedule was included, the phage pool dropped markedly in titer after the first 12 hours, followed by recovery over the next 24 hours, after which the phage were maintained at a roughly stable titer. Sequence analysis of single phage clones from the pool after 48 hours showed the strong enrichment of either tyrosine (3 mutations) or tryptophan (2 mutations) at position 87. While the ability of HA4_{Y87W} to interact with the SH2 domain was not previously reported, the evolution of these 2 amino acids strongly suggests functional significance. These results collectively demonstrate that PPI-PACE can be integrated with enhancements of improved mutagenesis and genetic drift, and can rapidly evolve novel PPIs from inactive starting materials in short timeframes.

Rationale for Novel Bt Toxin Interaction

[0155] Among the pests susceptible to Cry1Ac, *Trichoplusia ni* (cabbage looper) has shown widespread resistance in

the field. Interestingly, Cry1Ac toxicity in *T. ni* is not mediated through cadherin-like receptor interaction, but instead relies on the ABC transporter ABCC2 and aminopeptidase N (APN1). Field resistance has been shown to occur with changes in either gene, further supporting a mechanism of action that relies on these receptors. In vitro analysis shows high binding affinity of Cry1Ac to these receptors, and no detectable interaction with *T. ni* cadherin-like receptor TnCAD3 (FIG. 2). For example, Sf9 insect cells expressing TnCAD3 are not susceptible to Cry1Ac-mediated toxicity, and TBR fragments of the wild-type receptor show no binding in vitro.

[0156] Using the aforementioned sequence analysis, residues known to be critical for Cry1Ac binding were grafted onto the homologous TBR fragment of *T. ni* (designated TnTBR variants). One mutant, TnTBR3, which carried the mutations M1433F/L1436S/D1437A, showed weak affinity to Cry1Ac as measured by gel filtration, ligand blotting, and Biacore. These mutations convert positions known to be important for binding to reflect the consensus of known TBRs from a number of susceptible Lepidopteran species. Using this intermediate, Bt variant proteins with high affinity to TnTBR3 and/or TnCAD3 were evolved.

Continuous Directed Evolution of Cry1Ac Variants With Novel Receptor Specificities

[0157] To enable the directed evolution of Cry1Ac, APs carrying differential length fragments of TnTBR3 fused to 434cI were constructed and assessed for transcriptional activation levels in the presence of various domains of Cry1Ac fused to RpoZ. Only full-length Cry1Ac (residues 1-690) showed activity towards the TnTBR3 fragments, with TnTBR3 fragment 3 (TnTBR3-F3) showing the greatest degree of transcriptional activation at ~8-fold. To assess if this low level of transcriptional activation was sufficient for PACE, was observed when an SP carrying the RpoZ-Cry1Ac fusion was constructed about 100-fold phage enrichment using a strain carrying the cognate TnTBR3-F3 AP, whereas a control SP lacking an RpoZ fusion was rapidly lost. These results confirm that the weak Cry1Ac/TnTBR3-F3 interaction is sufficient for phage enrichment, and may enable continuous evolution in PACE.

[0158] 528 hours of PACE were performed using the bacterial 2 hybrid (B2H) selection in four segments (Round 1-4) specifying varying levels of both mutagenesis and selection stringency (FIGS. 3-7, Table 1). To modulate mutagenesis in the system, MP4 was used during TnTBR3 PACE experiments, as the starting material demonstrates weak binding (FIGS. 4-5). Mutagenesis was not greatly enhanced, so as to avoid mutations that destroy the ability of Cry1Ac to kill insects. Later evolutions using TnCAD3 exclusively used MP6, a mutagenesis platform with greater potency and broader mutational spectrum than MP4 (FIGS. 6-7). Further, the selection stringency was varied by increasing

the lagoon flow rate and strictly controlling the number of TnTBR3/TnCAD3 fragments participating in Cry1Ac variant recognition through engineering variants of the 434cI repressor and operator(s). At the end of every 120-144 hours segment, the ability of single clones to activate transcription on either TnTBR3 or TnCAD3 was assayed.

[0159] Single clone sequencing at the end of the first segment (132 hours) showed a strong consensus of two coding mutations in Cry1Ac, and 1 coding mutation in RpoZ (FIG. 4). All mutations together resulted in a 11-fold improvement over activation using the wild-type RpoZ-Cry1Ac fusion. This consensus clone was used for further evolution. At the end of the second segment (264 hours), even greater degrees of transcriptional activation were observed, reaching up to 20-fold above the starting fusion protein. Despite numerous genotypic changes occurring after this segment, no clear consensus emerged. Thus further evolutions utilized the pool derived from 264 h of PACE using the TnTBR3. After an additional 120 hours of PACE using an AP that carried TnCAD3-F3 and MP6, Cry1Ac variants with greatly enhanced affinity for TnCAD3, as assessed by the B2H were identified (FIG. 6). Mutations present in Cry1Ac are shown in Table 1 (below). Whereas the wild-type toxin doesn't activate transcription when using TnCAD3, single variants from 384 hours of PACE robustly activated transcription, reaching up to 210-fold above background. A further 144 hours using a more stringent AP yielded clones that could activate transcription by up to 500-fold (FIG. 7). Collectively, these results reveal the robust nature of the B2H-PACE platform, as it enables the evolution of protein-protein interactions in the absence of any detectable affinity between the starting materials.

[0160] Table 1 below provides a list of mutations that were observed during the four-round PACE experiment described above. Residues are listed in ascending order from top to bottom, left to right and correspond to the residues in the RpoZ-Cry1Ac chimera (SEQ ID NO: 3), in which amino acid positions 1-104 represent the linear amino acid positions in the RpoZ and the remaining amino acids from position 105 -712 correspond to the Cry1Ac amino acids as set forth in SEQ ID NO:1. For ease of reference, groups of mutations relating to the same residue have the same shading and are shown consecutively. To identify the corresponding amino acid position in SEQ ID NO:1, reduce the number shown in each row in Table 1 for each substitution by 104. For example, amino acid variant D487Y in Table 1 below corresponds to amino acid variant D383Y in SEQ ID NO: 1. Silent changes to the applicable codon for each amino acid position, if any, are also represented. For example, C113C represents a nucleotide sequence change introduced by PACE in the Cry1Ac coding sequence but which did not alter the naturally occurring amino acid at that position.

TABLE 1

Amino Acid Sequence Changes in CrylAc Produced By PACE.												
Without Off-Set												
N106N	I141S	V181V	P224L	R276R	G317G	G385C	F431Y	I476T	G528G	G593G	H643Y	S685S
N109N	I141T	I183V	P224S	V278V	E319E	G385D	S432L	I476L	F529F	P594S	H643H	S685L
I110I	S144S	I183T	T225A	V280V	E319D	S386L	E435G	G477G	S530S	G595G	N645S	L686L
I110V	S144L	I183L	N226S	V280M	R320S	A387A	F436F	I478T	H531H	T597I	V646I	G687G
E112D	L145L	E184G	P227S	V280A	V321I	Q388R	T437A	I478L	L533L	G598G	V646V	V690V
E112K	T146T	I187I	A228E	G282G	V321A	G389G	F438F	I478M	V536V	G599G	N647D	G691S
C113Y	L150L	I187T	A228A	R284K	G323G	G389D	P439P	N479N	R540R	L601L	N647S	G691D
C113F	S151N	N188D	A228S	R284G	P324P	G389V	P439S	N479K	R540H	V602V	N647N	V692I
C113R	E152E	Q189R	A228V	G286G	D325D	R392G	Y441Y	Q481Q	G542G	L604L	N647K	R693G
C113C	F153F	E192G	L229L	D288N	D328N	S393S	G442G	L483L	F543L	N605N	G649G	R693K
I114L	V154I	E192A	L229S	A290V	D328Y	I394I	T443T	L486L	N545N	S606R	N650S	R693R
Y116S	V154V	E193G	E231K	A290S	Y332H	I394L	M444V	D487Y	S546G	S607S	N650D	N694S
N117S	V154G	E193D	E231A	A290A	Y332Y	R395R	A445V	T489A	S546I	G608G	N650T	N694H
C118W	V154A	A195T	E232K	A290E	N333N	S396N	A445G	E490D	S547G	N609H	S651L	F695S
C118R	P155P	R196K	M233I	T291A	L339L	S396G	N446T	A492T	V548I	N609D	S652P	G697R
L119S	G156S	N197T	I235V	N293N	T340T	P397P	A447E	S496S	S549N	I611I	I653V	G697G
L119L	A157V	N197N	Q236R	S294R	T342T	N404L	A448V	N498S	S549S	Q612Q	T657I	T698I
S120R	G158G	N197D	D239D	S294G	L344L	S405G	A448T	N498T	I550V	R614K	P659P	T698P
S120G	L161L	N197S	M240I	S294S	D345D	S405S	A448D	N498I	F556C	R614G	P659S	A699V
N121N	G162G	Q198Q	N241S	R295C	I346I	S405R	A448A	A502A	I559V	Y616C	A660V	A699A
P122T	V164A	A199A	N241D	N297D	V347I	I406V	P449L	V503V	I559I	Y616S	A662S	V701V
P122H	V164V	I200I	S242G	N297N	V347V	I406M	Q450K	Y504Y	I559M	Y616Y	A662T	I702V
E123E	D165D	S201Y	S242N	D298N	A348S	T407N	Q450R	R505R	R561R	E618G	T663T	I702R
V124V	D165N	S201F	A243T	L299L	L349L	T407K	I453V	K506R	A563A	E618K	T663M	D704D
E125E	I166V	L203L	A243V	T300A	P351L	I408V	A455V	S507C	E564K	E618D	S664L	R705R
V126A	I166T	E204G	T245A	R301K	S355N	T410T	A455T	C507C	E564G	V619V	L665L	I709L
V126L	I166I	E204E	T246P	R301G	R356K	A412T	Q456H	C507F	N566S	V619I	N667D	I709I
V126V	I166K	E204I	T246A	L302I	R357K	H413H	L457L	S507N	I569I	I621I	L668L	V711V
G128D	I167I	G205G	T246S	I303I	R357R	H413Y	G458G	S507I	A570T	I621V	Q669R	V711A
G128S	I167V	G205R	A247T	G304V	R357I	G415G	G460G	T509T	S573S	I621R	S670L	V711S
G129R	I167M	G205V	A247D	G304G	I360I	G415D	R463K	T509M	I574I	H622H	S671S	
E130K	I167T	L206L	P249S	N305H	V363V	Y416C	T464I	V510A	A579V	F623F	D672N	
E130G	G169G	N208N	L250L	N305S	Q365Q	Y416H	T464T	V510V	V580M	T626I	Y675H	
R131S	I170I	I212I	V253A	Y306H	E369K	Y416Δ	L465F	S512S	V580V	T626P	Y675F	
I132T	I170T	I212V	V253V	T307T	Y371Y	Y417C	N465T	L513M	G582G	S627P	F676L	
E133K	I170V	I212T	N255D	Y309Y	N373S	S420S	S466P	D514G	N583N	S627S	E677G	
E133A	F171S	E215G	Y256H	A310V	N373N	G421G	S466L	I516I	N583K	R629K	S678S	
T134A	F171L	S216Y	V258V	V311V	E377A	Q423Q	S466S	I516V	F584L	R629R	A679T	
T134I	G172G	R218R	V258A	V311I	E377E	Q423R	S467S	P517P	F584S	V632I	A679S	
G135G	P173S	E219K	L260L	R312L	N378D	I424L	T468I	P518T	F584C	V634I	A679A	
G135V	P173T	E221D	Y264H	R312R	F379F	M425K	T468S	N520D	G588G	V634V	A681T	
G135D	S174F	E221G	V265I	R312H	G381G	S426S	R472R	N522S	S589S	Y636Y	A681V	
Y136C	F177S	E221E	Q266Q	Y314F	S382N	A426S	R472S	V523V	V590I	A637V	A681D	
Y136Y	A178T	A222T	A267T	Y314S	F383F	S427S	R472K	P524L	I591I	V639A	T683A	
Y136S	A178V	A222S	N269N	N315N	F383I	S427A	N475S	R526K	I591V	V639I	T683T	
T137A	F179L	A222A	L272L	N315D	R384R	V429A	N475T	Q527K	S592P	T640A	S684F	
D140D	L180F	D223D	S273S	T316A	G385S	G430G	N475Y	Q527P	S592L	T640N	S684Y	
Relative to SEQ ID NO: 1												
I6V	I37S	V77V	P120L	R172R	G213G	G281C	F327Y	I372T	G424G	G489G	H539Y	S581S
E8D	I37T	I79V	P120S	V174V	E215E	G281D	S328L	I372L	F425F	P490S	H539H	S581L
E8K	S40S	I79T	T121A	V176V	E215D	S282L	E331G	G373G	S426S	G491G	N541S	L582L
C9Y	S40L	I79L	N122S	V176M	R216S	A283A	F332F	I374T	H427H	T493I	V542I	G583G
C9F	L41L	E80G	P123S	V176A	V217I	Q284R	T333A	I374L	L429L	G494G	V542V	V586V
C9R	T42T	I83I	A124E	G178G	V217A	G285G	F334F	I374M	V432V	G495G	N543D	G587S
I10L	L46L	I83T	A124A	R180K	G219G	G285D	P335P	N375N	R436R	L497L	N543S	G587D
Y12S	S47N	N84D	A124S	R180G	P220P	G285V	P335S	N375K	R436H	V498V	N543N	V588I
N13S	E48E	Q85R	A124V	G182G	D221D	R288G	Y337Y	Q377Q	G438G	L500L	N543K	R589G
C14W	F49F	E88G	L125L	D184N	D224N	S289S	G338G	L379L	F439L	N501N	G545G	R589K
C14R	V50I	E88A	L125S	A186V	D224Y	I290I	T339T	L382L	N441N	S502R	N546S	R589R
L15S	V50V	E89G	E127K	A186S	Y228H	I290L	M340V	D383Y	S442G	S503S	N546D	N590S
S16R	V50G	E89D	E127A	A186A	Y228Y	R291R	A341V	T385A	S442I	G504G	N546T	N590H
S16G	V50A	A91T	E128K	A186E	N229N	S292N	A341G	E386D	S443G	N505H	S547L	F591S
P18T	P51P	R92K	M129I	T187A	L235L	S292G	N342T	A388T	V444I	N505D	S548P	G593R
P18H	G52S	N93T	I131V	N189N	T236T	P293P	A343E	S392S	S445N	I507I	I549V	G593G
V22A	A53V	N93N	Q132R	S190R	T238T	N300L	A344V	N394S	S445S	Q508Q	T553I	T594I

TABLE 1-continued

Relative to SEQ ID NO: 1												
V22L	G54G	N93D	D135D	S190G	L240L	S301G	A344T	N394T	I446V	R510K	P555P	T594P
G24D	L57L	N93S	M136I	S190S	D241D	S301S	A344D	N394I	F452C	R510G	P555S	A595V
G24S	G58G	Q94Q	N137S	R191C	I242I	S301R	A344A	A398A	I455V	Y512C	A556V	A595A
G25R	V60A	A95A	N137D	N193D	V243I	I302V	P345L	V399V	I455I	Y512S	A558S	V597V
E26K	V60V	I96I	S138G	N193N	V243V	I302M	Q346K	Y400Y	I455M	Y512Y	A558T	I598V
E26G	D61D	S97Y	S138N	D194N	A244S	T303N	Q346R	R401R	R457R	E514G	T559T	I598R
R27S	D61N	S97F	A139T	L195L	L245L	T303K	I349V	K402R	A459A	E514K	T559M	D600D
I28T	I62V	L99L	A139V	T196A	P247L	I304V	A351V	S403C	E460K	E514D	S560L	R601R
E29K	I62T	E100G	T141A	R197K	S251N	T306T	A351T	C403C	E460G	V515V	L561L	I605L
E29A	I62I	E100E	T142P	R197G	R252K	A308T	Q352H	C403F	N462S	V515I	N563D	I605I
T30A	I62K	E100I	T142A	L198I	R253K	H309H	L353L	S403N	I465I	I517I	L564L	V607V
T30I	I63I	G101G	T142S	I199I	R253R	H309Y	G354G	S403I	A466T	I517V	Q565R	V607A
G31V	I63V	G101R	A143T	G200V	R253I	G311G	G356G	T405T	S469S	I517R	S566L	V607S
G31D	I63M	G101V	A143D	G200G	I256I	G311D	R359K	T405M	I470I	H518H	S567S	S580Y
Y32C	I63T	L102L	P145S	N201H	V259V	Y312C	T360I	V406A	A475V	F519F	D568N	F75L
Y32Y	G65G	N104N	L146L	N201S	Q261Q	Y312H	T360T	V406V	V476M	2I52T	Y571H	A118A
Y32S	I66I	I108I	V149A	Y202H	E265K	Y312A	L361F	S408S	V476V	T522P	Y571F	L168L
T33A	I66T	I108V	V149V	T203T	Y267Y	Y313C	N361T	L409M	G478G	S523P	F572L	N211D
L76F	I66V	I108T	N151D	Y205Y	N269S	S316S	S362P	D410G	N479N	S523S	E573G	R280R
D119D	F67S	E111G	Y152H	A206V	N269N	G317G	S362L	I412I	N479K	R525K	S574S	V325A
S169S	F67L	S112Y	V154V	V207V	E273A	Q319Q	S362S	I412V	F480L	R525R	A575T	N371T
T212A	G68G	R114R	V154A	V207I	E273E	Q319R	S363S	P413P	F480S	V528I	A575S	Q423K
G281S	P69S	E115K	L156L	R208L	N274D	I320L	T364I	P414T	F480C	V530I	A575A	S488P
G326G	P69T	E1170	Y160H	R208R	F275F	M321K	T364S	N416D	G484G	V530V	A577T	T536A
N371Y	S70F	E117G	V161I	R208H	G277G	S322S	R368R	N418S	S485S	Y532Y	A577V	S580F
Q423P	F73S	E117E	Q162Q	Y210F	S278N	A322S	R368S	V419V	V486I	A533V	A577D	
S488L	A74T	A118T	A163T	Y210S	F279F	S323S	R368K	P420L	I487I	V535A	T579A	
T536N	A74V	A118S	N165N	N211N	F279I	S323A	N371S	R422K	I487V	V535I	T579T	

Analysis of PPI-PACE Evolved CrylAc Variants

[0161] Analysis of single clones from 528 hours highlighted a number of consensus genotypes, encoding proteins that contained from 9 to 14 amino acid sequence changes, most of which localized to the predicted cadherin-binding surface of CrylAc (domain II). Oligotyping analysis of long-read sequencing data revealed plausible evolutionary trajectories over the entire course of the experiment (FIGS. 20A-20C). While PACE does not explicitly promote recombination as a mechanism of gene diversification, multiple putative recombination events were observed during the course of CrylAc evolution (FIGS. 20A-20C). These recombination events, which may arise from multiple phage occasionally infecting the same host cell, yielded seminal, highly functional new variants.

[0162] Trypsin-activated CrylAc consensus variants showed robust activity in insect-based assays with Sf9 cells expressing the full-length wild type TnCAD3 receptor (FIG. 11). Furthermore, purified activated CrylAc variants showed very high binding affinity ($K_d = 18-34$ nM) to a TnCAD fragment containing the TBR (TnCAD-FL), highlighting the ability of B2H-PACE to evolve nanomolar protein binders in as short as three weeks (FIG. 14). Consensus amino acid sequence variants demonstrated trypsin sensitivity under conditions in which wild-type CrylAc was highly stable, suggesting the PACE evolved consensus variants

were proteolytically unstable (FIG. 10). All consensus variants affected *T. ni* larval viability in diet bioassays, but less potently than the wild-type CrylAc starting material (FIG. 12). To improve the stability of the evolved CrylAc variants, two orthogonal approaches were investigated: combinatorial mutation reversion analysis of evolved consensus variants and removal of destabilizing factors in the PACE strain.

[0163] Reversions were conducted on variants exhibiting the fewest number of amino acid sequence changes, for example, CrylAc_C05 which contained 9 amino acid changes. Later reversion analysis included consensus variants containing as many as 14 amino acid changes. Using this combinatorial approach, variants having improved properties, for example approaching the stability of wild type CrylAc (as measured by melting analysis and proteolytic stability) while retaining binding affinity to TnCAD3 were identified.

Improved CrylAc Binding Using Continuous Directed Evolution

[0164] Several consensus CrylAc variants containing mutations that were found in multiple PACE-evolved clones were designed, synthesized in expression vectors, expressed in *Bt*, purified and tested in multiple assays. These consensus CrylAc variants are listed in Table 2.

TABLE 2

Consensus Amino Acid Variants in Cry1Ac1. Mutations present in all 6 consensus variants are in bold.	
Consensus PACE evolved Cry1Ac1 variant:	Amino Acid Sequence Changes in Cry1Ac1
VP528_Blue (Cry1Ac1_C02)	Cry1Ac1_D383Y_S403C_E460K_N462S_E331G_T303N_A343E_T360I_S581L_F67S_G285D_C14W
VP528_Blue_Red (Cry1Ac1-C03)	Cry1Ac1_D383Y_S403C_E460K_N462S_T303N_A343E_T360I_S581L_C14W_M321K_Q352H_F67S_G285D_E331G
VP_Blue_minus (Cry1Ac1-C05)	Cry1Ac1_D383Y_S403C_C14W_T303N_A343E_T360I_E460K_N462S_S581L
VP_Red_plus (Cry1Ac1-C09)	Cry1Ac1_D383Y_S403C_R197G_S362P_N416D_E331G_E460K_N462S_S581L_T385A
VP528_Red (Cry1Ac1-A01)	Cry1Ac1_D383Y_S403C_E460K_N462S_T303N_A343E_T360I_S581L_C14W_M321K_Q352H
VP_Red (Cry1Ac1-A02)	Cry1Ac1_D383Y_S403C_R197G_S362P_N416D_E331G_E460K_N462S_S581L

Activity of PACE Derived Cry1Ac1 Amino Acid Sequence Variants in Cell-Based Assays

[0165] PACE derived Cry1Ac1 variants were tested for relative toxicity in insect cell-based assays. Lawns of Sf9 cells, engineered to express cadherin CAD3 from *T. ni* (cabbage looper, FIG. 11, Table 3) or *Chrysodeixis includens* (Table 4), were overlaid with a composition containing membrane-impermeable Sytox Green dye and PACE derived Cry1Ac1 variants pre-treated with trypsin to release the three-domain toxic core. Variants which bind to cadherin receptors aggregate to form pores, allowing the dye to enter the compromised cell membrane, binding to DNA and causing intense green fluorescence.

[0166] The toxicity of Cry1Ac1 and its variants to Sf9 cells expressing *T. ni* (cabbage looper) cadherin, was measured by increased fluorescence intensity of Sytox Green dye (FIG. 11) Short names for consensus PACE-evolved variants (C02, C03, C05, C09, A01 and A02) are used (see Table 2). Stabilized and non-stabilized (“unstable”) variants were tested. FIG. 11 also shows Kd values.

[0167] Tables 3 and 4 illustrate the toxicity of Cry1Ac1 and its variants to Sf9 cells expressing *C. includens* (*Chrysodeixis includens*, soybean looper) cadherin and *T. ni* (cabbage looper) cadherin, as measured by increased relative fluorescence intensity of Sytox Green dye. Protein concentrations are shown for each toxin. Short names for consensus PACE-evolved variants (C02, C03, C05, C09, A01 and A02) from Table 2 are used. Each data point is a mean of three measurements, with SD shown.

[0168] The data indicate that consensus PACE-evolved variants are much more active than the wild-type Cry1Ac1, despite being tested at lower doses.

TABLE 3

Toxicity of PACE-evolved variants to Sf9 cells expressing T. ni cadherin.		
	Relative fluorescence	Standard deviation
Buffer	473	22
Empty vector	766	113
Cry1Ac1, 28 ug/ml	549	90
Cry1Ac1_D384Y_S404C, 16ug/ml	1041	61
Cry1Ac1-C02, 7 ug/ml	6939	120
Cry1Ac1-C03, 4 ug/ml	7590	455
Cry1Ac1-C05, 9 ug/ml	8189	708
Cry1Ac1-C09, 3 ug/ml	4929	281
Cry1Ac1-A01, 4 ug/ml	10591	613
Cry1Ac1 A02, 1 ug/ml	5425	385

TABLE 4

Toxicity of PACE-evolved variants to Sf9 cells expressing C. includens cadherin.		
	Relative fluorescence	Standard deviation
Buffer	546	191
Empty vector	407	70
Cry1Ac1, 28 ug/ml	116	47
Cry1Ac1_D384Y_S404C, 16ug/ml	180	115
Cry1Ac1-C02, 7 ug/ml	4468	697
Cry1Ac1-C03, 4 ug/ml	3425	624
Cry1Ac1-C05, 9 ug/ml	3391	69
Cry1Ac1-C09, 3 ug/ml	3286	649
Cry1Ac1-A01, 4 ug/ml	4287	572
Cry1Ac1 A02, 1 ug/ml	3642	284

Consensus PACE Variants Are Susceptible to Proteolysis

[0169] This example demonstrates the susceptibility of consensus PACE variants to trypsinolysis. As shown in FIG. 10, following trypsin treatment, an SDS gel band at 66 kDa, the trypsin core (presumably the active three-domain Bt toxin), is visibly present on for the wild-type Cry1Ac1 and double mutant forms of the protein. Almost no visible core toxin is seen in the SDS gels for the PACE-derived Cry1Ac consensus variants.

[0170] The upper panel of FIG. 10 shows an SDS gel with solubilized Bt spore/crystal mixtures (S) and trypsin-treated (T) consensus PACE-evolved Cry1Ac1 variants. The band of the toxic core size is pointed to with the red arrow. EV: Empty vector control; DM:Double mutant Cry1Ac1_D384Y_S404C.

Improved Stability of PACE-Derived Cry1Ac1 Variants

[0171] In order to improve the proteolytic stability of consensus PACE variants while maintaining activity via combinatorial, combinatorial reversal of PACE-evolved mutations back to the wild type residues was attempted. First, 5 mutations were reversed that were present in all consensus variants (invariable consensus) in Table 2 (in bold), using consensus variants Cry1Ac1_C05 and Cry1Ac1_C09. That set also include a construct that include just the minimum, or invariable consensus (Cry1Ac1_D383Y_S403C_E460K_N462S_S581L). This set included 13 variants.

[0172] Next, all possible combinations of reversal mutations for consensus PACE variants Cry1Ac1_C03, Cry1Ac1_C05 and Cry1Ac1_A01 were designed - a total of 276 variants, of which 180 variant genes were generated, for a total of 191 variants.

[0173] Of the total of 191 generated variants, 190 variants were expressed in Bt, of which 141 variants formed a stable ~66 kDa core upon treatment with trypsin. An example of SDS gel with trypsin-treated CryIAc1 variants is shown in the lower panel of FIG. 10, showing an SDS gel for the wild-type CryIAc1 (well G3), consensus PACE-evolved variant CryIAc1_CO5 and various “stabilization” CryIAc1 variants.

[0174] CryIAc1 variants that form a stable core of ~66 kDa in the presence of trypsin were further screened in cell-based assay with insect cells Sf9 expressing *T. ni* cadherin receptor, to select CryIAc1 variants that retained ability for functional binding to cadherin leading to cell membrane disruption. An example of the data from such test is shown in FIG. 15, illustrating the screening of CryIAc1 variants (solubilized and trypsinized Bt spore/crystal mixtures) for toxicity to Sf9 cells expressing *T. ni* cadherin expressed as relative fluorescence caused by influx of SytoxGreen fluorescent dye into cells as result of toxin-induced membrane disruption.

[0175] Fifteen variants with the highest activity in cell-based assay were selected for protein purification using column chromatography on Superdex Q (ion-exchange) and HiLoad Superdex 200 (size exclusion) columns, and are listed in Table 5.

TABLE 5

Stabilized CryIAc1_PACE variants selected for column chromatography purification and detailed functional analysis.	
Name	Amino Acid Changes in CryIAc1
CryIAc1_pace_mut_0106	D383Y, S403C, C14W, T360I, N462S, S581L
CryIAc1_pace_mut_0085	D383Y, S403C, T303N, T360I, E460K, N462S
CryIAc1_CO5_Y384D_C404S	C14W, T303N, A343E, T360I, E460K, N462S, S581L
CryIAc1_A01_Y384D_C404S	C14W, T303N, M321K, A343E, Q352H, T360I, E460K, N462S, S581L
CryIAc1_CO3_Y384D_C404S	C14W, F67S, G285D, T303N, M321K, E331G, A343E, Q352H, T360I, E460K, N462S, S581L
CryIAc1_pace_mut_0133	E460K, N462S, E331G, T303N, A343E, T360I, S581L, F67S, G285D, C14W
CryIAc1_pace_mut_0263	T360I, E460K, S581L
CryIAc1_pace_mut_0050	D383Y, S403C, C14W, T360I, E460K
CryIAc1_pace_mut_0169	T303N, E460K
CryIAc1_pace_mut_0038	D383Y, S403C, T303N, T360I
CryIAc1_pace_mut_0255	T303N, N462S, S581L
CryIAc1_pace_mut_0001	D383Y, S403C, C14W
CryIAc1_pace_mut_0170	T303N, N462S
CryIAc1_pace_mut_0127	S403C, E460K, N462S, T303N, A343E, T360I, S581L, C14W, M321K, Q352H, F67S, G285D, E331G
CryIAc1_pace_mut_0097	D383Y, S403C, C14W, A343E, T360I, S581L

[0176] These purified proteins were tested for thermal stability in protein melting assay (FIG. 13), tightness of in vitro binding (FIG. 14), and toxicity in cell-based assay with Sf9 cells expressing *T. ni* cadherin (FIG. 16).

[0177] FIG. 13 illustrates data from a protein melting assay with purified “stabilization” consensus PACE-evolved CryIAc1 variants.

[0178] FIG. 14 illustrates data from in vitro binding of purified stabilized consensus PACE-evolved CryIAc1 variants to toxin-binding domain TBR3 from the *T. ni* cadherin, immobilized on a ForteBio chip via His-tag.

[0179] FIG. 16 illustrates the toxicity of purified CryIAc1 consensus CryIAc1 PACE-evolved variant CryIAc1_CO3 and stabilized consensus CryIAc1 PACE-evolved variants (at 10 µg/ml), to Sf9 cells expressing *C. includens* cadherin.

In Vivo Activity of Evolved CryIAc Variants

[0180] Based on combination of the above-described assays, three CryIAc1 variants were selected for diet bioassays with *T. ni* and *C. includens*. These variants are listed in Table 6. Diet bioassays were performed with Bt spore/crystal mixtures isolated from sporulated and lysed Bt cultures.

TABLE 6

Stabilized consensus CryIAc1 amino acid sequence variants selected for insect bioassay testing.	
Stabilized CryIAc1 variant	Mutations in CryIAc1
CryIAc1_CO5_Y384D_C404S	C14W, T303N, A343E, T360I, E460K, N462S, S581L
CryIAc1_CO3_Y384D_C404S	C14W, F67S, G285D, T303N, M321K, E331G, A343E, Q352H, T360I, E460K, N462S, S581L
CryIAc1_A01_Y384D_C404S	E460K, N462S, T303N, A343E, T360I, S581L, C14W, M321K, Q352H

[0181] Results of diet bioassay with *C. includens* and *T. ni* are shown in FIGS. 17-19 and in Table 7, illustrating the activity (mortality and growth inhibition) of stabilized consensus PACE-evolved CryIAc1 variants (sucrose gradient purified Bt crystals) in diet bioassay. Numbers above bars in FIG. 17 and d18 are stunting scores (maximum stunting score - 3). Letters below bars are for mortality T-grouping.

[0182] To characterize the species profile of their insecticidal activity, the evolved CryIAc variants were tested in diet bioassays on 11 additional agricultural pests: a lepidopteran related to *T. ni* (*Chrysodeixis includens*, soybean looper) that encodes a cadherin-like receptor highly homologous to TnCAD, eight more distantly related lepidopteran pests (*Heliothis virescens*, tobacco budworm; *Helicoverpa zea*, corn earworm; *Plutella xylostella*, diamondback moth; *Agrotis ipsilon*, black cutworm; *Spodoptera frugiperda*, fall armyworm; *Anticarsia gemmatilis*, velvetbean caterpillar; *Diatraea saccharalis*, sugarcane borer; and *Spodoptera eridania*, southern armyworm), and three non-lepidopteran pests (*Leptinotarsa decemlineata*, Colorado potato beetle; *Lygus lineolaris*, tarnished plant bug; and *Diabrotica virgifera*, western corn rootworm) (FIG. 21 and FIG. 22). Data indicates that the stabilized evolved CryIAc variants were more potent than wild-type CryIAc against *C. includens*, and comparably potent as wild-type CryIAc against the other lepidopteran pests assayed (FIG. 21). Neither the evolved nor wild-type CryIAc exhibited insecticidal activity against the lepidopteran *S. eridania* or the three non-lepidopterans tested. These results further support the mechanism of action of the PACE-evolved Bt toxins as binding to the cadherin receptor in *T. ni* and the related cadherin receptor in *C. includens*, while retaining binding to native receptors in all tested lepidopteran species. These data also reveal that the evolved Bt toxins did not acquire activity against species lacking a receptor homologous to TnCAD. Taken together, these findings demonstrate that an evolved Bt toxin that binds a novel target can potentially kill closely related insect pest species, while maintaining a similar overall insect spectrum specificity as the parental Bt toxin.

[0183] As evident from the data presented herein, stabilized CryIAc1 variants are not only much more active than consensus PACE-evolved variants, but also more active than the wild-type CryIAc1.

TABLE 7

Insecticidal activity of PACE-evolved and stabilized variants against Cry1Ac-resistant and susceptible <i>T. ni</i> .							
		Toxin	LC50	95% CL	Slope	SE	Relative potency (%)
Susceptible <i>T. ni</i>	Response: Mortality	Cry1Ac	0.039	0.019 - 0.069	2.54	0.26	100
		Protein 1	0.793	0.505 - 1.082	2.84	0.41	5
		Protein 2	0.715	0.407- 1.176	1.78	0.22	5
		Protein 3	0.035	0.026 - 0.045	3.59	0.41	111
		Protein 4	0.018	0.014 - 0.020	4.68	0.75	217
		Protein 5	0.021	0.015 - 0.024	4.82	1.09	186
	Response: growth inhibition	Toxin	IC50	95% CL	Slope	SE	Relative potency (%)
		Cry1Ac	0.019	0.011- 0.027	3.09	0.39	100
		Protein 1	0.136	0.110- 0.160	4.00	0.62	14
		Protein 2	0.217	0.167- 0.268	2.59	0.32	9
		Protein 3	0.016	0.014- 0.018	5.53	0.82	119
		Protein 4	0.007	0.003 - 0.010	3.65	0.61	271
Cry1Ac resistant <i>T. ni</i>	Response: Mortality	Toxin	LC50	95% CL	Slope	SE	Relative potency (%)
		Cry1Ac	51.229	9.929 - 90.241	1.89	0.36	100
		Protein 1	408.713	263.629 - 680.973	0.81	0.10	13
		Protein 2	235.698	79.467 - 510.323	1.12	0.15	22
		Protein 3	1.938	1.550- 2.352	2.55	0.29	2643
		Protein 4	1.841	1.390- 2.312	2.25	0.28	2783
	Response: growth inhibition	Protein 5	0.153	0.046 - 0.289	2.01	0.22	33483
		Toxin	IC50	95% CL	Slope	SE	Relative potency (%)
		Cry1Ac	23.402	4.587 - 46.512	1.49	0.25	100
		Protein 1	56.626	40.600 - 75.685	1.84	0.21	41
		Protein 2	47.232	20.236 - 90.729	1.16	0.12	50
		Protein 3	1.116	0.797 - 1.484	2.19	0.23	2097
		Protein 4	0.733	0.515 - 0.949	2.06	0.28	3193
		Protein 5	0.083	0.061- 0.104	2.57	0.38	28195

SEQUENCES

[0184] It will be understood that the sequences provided herein are exemplary and that they are disclosed herein to illustrate some embodiments of the present disclosure. They are neither meant to be limiting to the disclosure, nor to limit the meaning of the terms “Cry1Ac” or “cadherin.” Those of ordinary skill in the art will understand that the sequences provided herein are exemplary only and will be able to ascertain additional suitable sequences, e.g., homologs and orthologs of *B. thuringiensis* Cry1Ac and *Trichoplusia ni* cadherin in *B. thuringiensis* and *Trichoplusia ni* as well as in other species.

[0185] *B. thuringiensis* Cry1Ac; protein sequence encoded by GenBank Accession No. AY730621 (residues 2-609) (SEQ ID NO: 1)

DNNPNINECIPYNCLSNPEVEVLGGERIETGYTPIDISLSLTQFLLSEFV
PGAGFVLGLVDI IWGIFGPSQWDAFLVQIEQLINQRIEEFARNQAI SRLE
GLSNLYQIYAESFREWEADPTNPALREEMRIQFNDMN SALT TAIP LFAVQ
NYQVPLLSVYVQAANLHLSVLRDVS VFGQRWGFDAATINSRYNDLTR LIG
NYTDYAVRWYNTGLERVWGPD SRDWVRYNQFRRELT LTVL DIVALF PNYD
SRRYP IRTVSQLTREI YTNPVLENFDG SFRGSAQGIERSIRSPHLM DILN
SITIYTDAHRGYYYWSGHQIMASPVGFSGP EFTFPLYGTMGNAAPQQRIV
AQLGQG VYRTL SSTLYRRPFNIGINNQQLSVLDGTEFAYGTSSNLPSAVY
RKSGTVDSLDEIPPQNNNVPPRQGF SHRLSHVSMFRSGFSNSSVSIIRAP
MFSWIHRSAEFNNI IASDSITQIPAVKGNFLNGSVISGPGFTGGDLVRL
NSSGNNIQNRGYIEVPIHFPSTSTRYRVRVRYASVTPIHLNVNWGNSSIF
SNTVPATATSLDNLQSSDFGYFESANAFTSSLGNIVGV RNFSGTAGVIID
RFEFIPVT

(Domain 1: 1-274 (pore formation); Domain 2: 275-462 (receptor binding); Domain 3: 463-608 (sugar binding)

[0186] RpoZ-Cry1Ac1_1 fusion - amino acid sequence

MARVTVQDAV EKIGNRFDLV LVAARRARQM QVGKGDPLVP EENDKTTVIA LREIEEGLIN
NQILDVRERQ EQQEQA AEL QAVTAIAEGR RAAAEQKLIS EEDLDNNPNI NECIPYNCLS
NPEVEVLGGE RIETGYTPID ISLSLTQFLL SEFVPGAGFV LGLVDI IWGI FGPSQWDAFL
VQIEQLINQR IEEFARNQAI SRLEGLSNLY QIYAESFREW EADPTNPALR EEMRIQFNDM
NSALT TAIP LFAVQNYQVPL LSVYVQAANL HLSVLRDVS VFGQRWGFDAATINSRYNDLT
RLIGNYTDYA VRWYNTGLER VWGPD SRDWV RYNQFRRELT LTVL DIVALF PNYDSRRYP I
RTVSQLTREI YTNPVLENFD G SFRGSAQGI ERSIRSPHLM DILNSITIYT DAHRGYYYWS
GHQIMASPVG FSGPEFTFPL YGTMGNAAPQ QRIVAQLGQG VYRTL SSTLY RRPFNIGINN

-continued

QQLSVLDGTE FAYGTSSNLP SAVYRKSGTV DSI~~DE~~I~~PP~~Q~~N~~ NNVPPRQ~~G~~FS HRLSHVSMFR
SGFSNSSVSI IRAPMFSWIH RSAEFNNIIA SDSITQIPAV KGNFLNGSV ISGPGFTGGD
LVRLNSSGNN IQNRGYIEVP IHFPSTSTRY RVRVRYASVT PIHLNVNWGN SSIFSNTVPA
TATSLDNLQS SDFGYFESAN AFTSSLGNIV GVRNFSGTAG VIIDRFEFIP VT* (SEQ ID NO:
3)

[0187] RpoZ-CrylAcl nucleotide sequence

atggcacgcgtaactgttcaggacgctgtagagaaaaattggtaaccgttt
tgacctggtaactggtcgccgcgcgtcgctcagatgcaggtaggcg
gaaaggatccgctggtaccggaagaaaacgataaaaccactgtaatcgcg
ctgcgcgaaatcgaagaaggtctgatcaacaaccagatcctcgacgttcg
cgaacgccaggaacagcaagagcaggaagccgctgaattacaagccgtta
ccgctattgctgaaggtcgtcgtgcggccgcggaacaaaagcttatttct
gaagaggacttgGATAACAATCCGAACATCAATGAATGCATTCCTTATAA
TTGTTTAAGTAACCCCTGAAGTAGAAGTATTAGGTGGAGAAAGAATAGAAA
CTGGTTACACCCCAATCGATATTTCTTGTGCTGCTAACGCAATTTCTTTTG
AGTGAATTTGTTCCCGGTGCTGGATTTGTGTTAGGACTAGTTGATATAAT
ATGGGGAATTTTTGGTCCCTCTCAATGGGACGCATTTCTTGTACAAATTG
AACAGTTAATTAACCAAAGAATAGAAGAATTCGCTAGGAACCAAGCCATT
TCTAGATTAGAAGGACTAAGCAATCTTTATCAAATTTACGCAGAATCTTT
TAGAGAGTGGGAAGCAGATCCTACTAATCCAGCATTAAGAGAAGAGATGC
GTATTC AATTCAATGACATGAACAGTGCCCTTACAACCGCTATTCCTCTT
TTTGCAGTTCAA AATTATCAAGTTCCTCTTTTATCAGTATATGTTCAAGC
TGCAAATTTACATTTATCAGTTTTGAGAGATGTTTCAGTGTTTGGACAAA
GGTGGGGATTTGATGCCGCGACTATCAATAGTCGTATAATGATTTAACT
AGGCTTATTGGCAACTATACAGATTATGCTGTACGCTGGTACAATACGGG
ATTAGAACG~~GT~~GTATGGGGACCGGATTCTAGAGATTGGGTAAGGTATAATC
AATTTAGAAGAGAATTAACACTA~~ACT~~GTATTAGATATCGTTGCTCTGTTC
CCGAATTATGATAGTAGAAGATATCCAATTCGAACAGTTTCCCAATTAAC
AAGAGAAATTTATACAAACCCAGTATTAGAAAATTTTGATGGTAGTTTTT
GAGGCTCGGCTCAGGGCATAGAAAGAAGTATTAGGAGTCCACATTTGATG
GATATACTTAACAGTATAACCATCTATACGGATGCTCATAGGGGTTATTA
TTATTGGTCAGGGCATCAAATAATGGCTTCTCCTGTAGGGTTTTTCGGGGC
CAGAATTCAC~~TTTT~~CCGCTATATGGA~~ACT~~TATGGGAAATGCAGCTCCACAA
CAACGTATTGTTGCTCAACTAGGTCAGGGCGTGTATAGAACATTATCGTC
CACTTTATATAGAAGAC~~TTTT~~AATATAGGGATAAATAATCAACAAC~~TAT~~
CTGTTCTTGACGGGACAGAATTTGCTTATGGAACCTCCTCAAATTTGCCA
TCCGCTGTATACAGAAAAAGCGGAACGGTAGATTTCGCTGGATGAAATACC
GCCACAGAATAACAACGTGCCACCTAGGCAAGGATTTAGTCATCGATTAA
GCCATGTTTCAATGTTTCGTTCAAGGCTTTAGTAATAGTAGTGTAAGTATA
ATAAGAGCTCCTATGTTCTCTTGGATACATCGTAGTGTGAATTTAATAA
TATAATTGCATCGGATAGTATTACTCAAATCCCTGCAGTGAAGGGAACT
TTCTTTTTAATGGTTCTGTAATTTCAGGACCAGGATTTACTGGTGGGGAC
TTAGTTAGATTAAATAGTAGTGGAATAACATTCAGAATAGAGGGTATAT
TGAAGTTCCAATTCAC~~TT~~CCCATCGACATCTACCAGATATCGAGTTTCGTG
TACGGTATGCTTCTGTAACCCCGATTCACTCAACGTTAATTGGGGTAAT
TCATCCATTTTTTCCAATACAGTACCAGCTACAGCTACGTCATTAGATAA
TCTACAATCAAGTGATTTTGGTATTTTGAAAGTGCCAATGCTTTTACAT
CTTCATTAGGTAATATAGTAGGTGTTAGAAATTTTAGTGGGACTGCAGGA
GTGATAATAGACAGATTTGAATTTATTCCAGTTACTtaa (SEQ ID NO:
4)

[0188] *Trichoplusia ni cadherin*, GenBank Accession No. AEA29692 (residues 1133-1582).

AGNTFRLSREQSTVNGVLVRVDGQSFPRVSATDE~~D~~GLHAGSVSFSVVGAA
AEYFSMRNFEDNTGELYLSQPLPLEDDGFDITIRGSDAGTEPGSLFSEVS
FRLVFVPTHGDPVFSVSQYTVAFIEKEAGLLESHQLPRAVDPKNYMCEEM
NEPCHEIYYSIIDNNEEGYFQVDSTTNVISLSRELERASQASHVVRVAAS
NTLLDPAAPPPLLPSS~~TF~~LLTINVREADPRPVFEREIYTAGIYETDTSNR
ELLTVHATHTEGLDITYTMDLDTMVVDPSLEGVRESAFTLHPSSGVLSLN
MNPLDTMVGMEF~~FD~~VVATDTRGAEARTDVKIY~~L~~ITHLNRVYFLFNNTLDV
VDSNRAFIADTFSSVFS~~LT~~CNIDAVLRAPDSSGAARD~~DR~~TEVRAHFIRNH
VPAT~~T~~DEIEQLRSNTILLRAIQETLLTRELHLEDFVGGSSPELGVDNSLT
(SEQ ID NO: 2)

[0189] *Trichoplusia ni cadherin* Fragment 3 of CAD3 (wild-type) amino acid sequence

RPVFEREIYTAGIYETDTSNRELLTVHATHTEGLDITYTMDLDTMVVDPS
LEGVRESAFTLHPSSGVLSLNMNPLDTMVGMEF~~FD~~VVATDTRGAEARTDV
KIYLITHLNRVYFLFNNTLDVVD~~S~~NRAFIADTFSSVFS~~LT~~CNIDAVLRAP
DSSGAARD~~DR~~TEVRAHFIRNHVPAT~~T~~DEIEQLRSNTILLRAIQETLLTRE
LHLEDFVGGSSPELGVDNSLT* (SEQ ID NO: 5)

[0190] *Trichoplusia ni cadherin* Fragment 3 of TBR3 mutant amino acid sequence

RPVFEREIYTAGIYETDTSNRELLTVHATHTEGLDITYTMDLDTMVVDPS
LEGVRESAFTLHPSSGVLSLNFNPSATMVGMEF~~FD~~VVATDTRGAEARTDV
KIYLITHLNRVYFLFNNTLDVVD~~S~~NRAFIADTFSSVFS~~LT~~CNIDAVLRAP
DSSGAARD~~DR~~TEVRAHFIRNHVPAT~~T~~DEIEQLRSNTILLRAIQETLLTRE
LHLEDFVGGSSPELGVDNSLT* (SEQ ID NO: 6)

EQUIVALENTS AND SCOPE, INCORPORATION BY REFERENCE

[0191] Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. The scope of the present invention is not intended to be limited to the above description, but rather is as set forth in the appended claims.

[0192] In the claims articles such as “a,” “an,” and “the” may mean one or more than one unless indicated to the contrary or otherwise evident from the context. Claims or descriptions that include “or” between one or more members of a group are considered satisfied if one, more than one, or all of the group members are present in, employed in, or otherwise relevant to a given product or process unless indicated to the contrary or otherwise evident from the context. The invention includes embodiments in which exactly one member of the group is present in, employed in, or otherwise relevant to a given product or process. The invention also includes embodiments in which more than one, or all of the group members are present in, employed in, or otherwise relevant to a given product or process.

[0193] Furthermore, it is to be understood that the invention encompasses all variations, combinations, and permutations in which one or more limitations, elements, clauses, descriptive terms, etc., from one or more of the claims or from relevant portions of the description is introduced into another claim. For example, any claim that is dependent on another claim can be modified to include one or more limitations found in any other claim that is dependent on the same base claim. Furthermore, where the claims recite a composition, it is to be understood that methods of using the composition for any of the purposes disclosed herein are included, and methods of making the composition according to any of the methods of making disclosed herein

range, unless the context clearly dictates otherwise. It is also to be understood that unless otherwise indicated or otherwise evident from the context and/or the understanding of one of ordinary skill in the art, values expressed as ranges can assume any subrange within the given range, wherein the endpoints of the subrange are expressed to the same degree of accuracy as the tenth of the unit of the lower limit of the range.

[0196] In addition, it is to be understood that any particular embodiment of the present invention may be explicitly excluded from any one or more of the claims. Where ranges are given, any value within the range may explicitly be excluded from any one or more of the claims. Any embodiment, element, feature, application, or aspect of the compositions and/or methods of the invention, can be excluded from any one or more claims. For purposes of brevity, all of the embodiments in which one or more elements, features, purposes, or aspects is excluded are not set forth explicitly herein.

[0197] All publications, patents and sequence database entries mentioned herein, including those items listed above, are hereby incorporated by reference in their entirety as if each individual publication or patent was specifically and individually indicated to be incorporated by reference. In case of conflict, the present application, including any definitions herein, will control.

SEQUENCE LISTING

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SEQ ID NO: 1             moltype = AA   length = 608  
FEATURE                  Location/Qualifiers  
source                   1..608  
                           mol_type = protein  
                           organism = Bacillus thuringiensis
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SEQ ID NO:	1						
DNNPNINECI	PYNCLSNPEV	EVLGGERIET	GYPIDISLS	LTQFLLSFV	PGAGFVLGLV		60
DIIWGIFGFS	QWDAFLVQIE	QLINQRIEEF	ARNQAISRLE	GLSNLYQIYA	ESFREWEADP		120
TNPALREEMR	IQFNDMNSAL	TTAIPLFAVQ	NYQVPLLSVY	VQAANLHLSV	LRDVSVFQQR		180
WGFDAATINS	RYNDLTRLIG	NYTDYAVRWY	NTGLERVWGP	DSRDWVRYNQ	FRRELTTLTVL		240
DIVALFPNYD	SRRYPIRTVS	QLTREIYTNP	VLENFDGSFR	GSAQGIERSI	RSPHLMIDILN		300
SITIYTDADR	GYYYWSGHQI	MASPVGFSGP	EFTFPLYGTM	GNAAPQQRIV	AQLGQGQVYRT		360
LSSTLYRRPF	NIGINNQQLS	VLDGTEFAYG	TSSNLPSAVY	RKSGTVDSL	EIPPQNNNVP		420
PRQGFSHRLS	HVSMFRSGFS	NSSVSIIRAP	MFSWIHRSAE	FNNIIASDSI	TQIPAVKGNF		480
LFNGSVISGP	GFTGGDLVRL	NSSGNNIQNR	GYIEVPIHFP	STSTRYRVRV	RYASVTPIHL		540
NVNWGNSSIF	SNTVPATATS	LDNLQSSDFG	YFESANAFTS	SLGNIVGVRN	FSGTAGVIID		600
RFEFIPVT							608

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SEQ ID NO: 2          moltype = AA   length = 450
FEATURE               Location/Qualifiers
source                1..450
                     mol_type = protein
                     organism = Trichoplusia ni
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SEQ ID NO: 2						
AGNTFRLSRE	QSTVNGVLVR	VDGQSFPVRV	ATDEDGLHAG	SVSFSVVGAA	AEYFSMRNFE	60
DNTGELYLSQ	PLPLEDDGFD	ITIRGSDAGT	EPGSLFSEVS	FRLVFPVPHG	DPVFSVSQYT	120
VAFIEKEAGL	LESHQLPRAV	DPKNYMCEEM	NEPCHEIYYS	IIDNNEEGYF	QVDSTTNVIS	180
LSRELERASQ	ASHVVRVAAS	NTLLDPAAPP	PLLPSSTFLL	TINVREADPR	PVFEREIYTA	240
GIYETDTSNR	ELLTVHATHT	EGLDITYTMD	LDTMVVDPSL	EGVRESAFTL	HPSSGVLSLN	300
MNPLDTMVMG	FEFDVVATDT	RGAEARTDVK	IYLITHLNRV	YFLFNNTLDV	VDSNRAFIAD	360
TFSSVFSLTC	NIDAVLRAPD	SSGAARDDRT	EVRAHFIRNH	VPATTDEIEQ	LRNNTILLRA	420
IQETLLTREL	HLEDFVGGSS	PELGVDNSLT				450

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SEQ ID NO: 3          moltype = AA  length = 712
FEATURE               Location/Qualifiers
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REGION              1..712
                    note = Synthetic Polypeptide
source              1..712
                    mol_type = protein
                    organism = synthetic construct

SEQ ID NO: 3
MARVTVQDAV EKIGNRFDLV LVAARRARQM QVGGKDPLVP EENDKTTVIA LREIEEGLIN 60
NQILDVRERQ EQQEQAEL QAVTAIAEGR RAAAEQKLIS EEDLDNNPNI NECIPYNCLS 120
NPEVEVLGGE RIETGYTPID ISLSLTQFLI SEFVPGAGFV LGLVDIIWGI FGPSQWDAFL 180
VQIEQLINQR IEEFARNQAI SRLEGLSNLY QIYAESFREW EADPTNPALR EEMRIQFNDM 240
NSALTTAIPF FAVQNYQVPL LSVYVQAANL HLSVLRDVSFV FGQRWGFDAF TINSRYNDLT 300
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                    note = Synthetic Polynucleotide
source              1..2139
                    mol_type = other DNA
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QLRSNTILLR	AIQETLLTRE	LHLEDFVGGG	SPELGVDNSL	T		221
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1-59. (canceled)

60. A method for producing a modified pesticidal protein, the method comprising introducing one or more mutations into a nucleic acid sequence encoding a receptor-binding domain of a pesticidal protein by phage-assisted continuous evolution (PACE) to obtain a modified nucleic acid sequence encoding the modified pesticidal protein, wherein the modified pesticidal protein binds a non-cognate receptor of a target pest.

61. The method of claim **60**, wherein the pesticidal protein is a *Bacillus thuringiensis* (Bt) toxin.

62. The method of claim **60**, wherein the non-cognate receptor comprises a toxin binding region (TBR).

63. The method of claim **60**, wherein the modified pesticidal protein comprises an amino acid sequence that is at least 90% amino acid sequence identical to a Cry 1 Ac protein having the amino acid sequence set forth in SEQ ID NO: 1.

64. The method of claim **60**, wherein the one or more mutations in the nucleic acid sequence result in a nonsense mutation, missense mutation, synonymous mutation, or non-synonymous amino acid substitution.

65. The method of claim **60**, wherein the modified pesticidal protein kills the target pest.

66. The method of claim **60**, wherein the pesticidal protein is Cry1Ac (SEQ ID NO: 1).

67. The method of claim 66, wherein the modified pesticidal protein binds the non-cognate receptor of the target pest with higher affinity than Cry 1 Ac.

68. The method of claim 66, wherein Cry 1 Ac does not bind to the non-cognate receptor of the target pest.

69. The method of claim 60, wherein the receptor binding domain comprises an amino acid sequence that is at least 90% identical to amino acid residues 275-462 of SEQ ID NO: 1.

70. The method of claim 60, wherein the non-cognate receptor is a cadherin or a cadherin-like receptor.

71. The method of claim 70, wherein the non-cognate receptor is a *Trichoplusia ni* cadherin receptor or a *Chrysodeixis includens* cadherin receptor.

72. The method of claim 60, wherein the modified pesticidal protein binds to a receptor comprising an amino acid sequence represented by SEQ ID NO: 2.

73. The method of claim 60, wherein the modified pesticidal protein binds to a receptor comprising an amino acid sequence represented by SEQ ID NO: 5.

74. The method of claim 60, wherein the modified pesticidal protein binds to a receptor comprising an amino acid sequence represented by SEQ ID NO: 6.

75. The method of claim 60, wherein the pest is a caterpillar, moth, beetle, fly, gnat, or mosquito.

76. The method of claim 60, wherein the pest is from insect order *Lepidoptera*, *Coleoptera*, *Diptera*, or *Hemiptera*.

77. The method of claim 60, wherein the modified pesticidal protein retains ability to bind to its native receptor of the target pest.

78. The method of claim 77, wherein the native receptor is ABC transporter ABCC2 or aminopeptidase N (APN1).

79. The method of claim 60, wherein the method further comprises reverting one or more mutations of the modified pesticidal protein obtained using PACE.

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